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The report describes the results of studies relating to an evaluation of the OMEGA navigation system with particular emphasis on airborne use. The Research Triangle Institute has worked very closely with Mr. E. M. Bracalente and Mr. C. D. Lytle of the Communications Research Branch under the direction of Mr. J. H. Schrader. Programming support at the Langley Research Center has been provided by Mr. L. J. Jowers of the LTV Aerospace Corporation under contract to NASA and assigned to this project. Some of the results presented are definitely the result of a team effort and cannot be attributed solely to the Research Triangle Institute. These have been included in this report to provide a comprehensive and coherent summary of the progress of the evaluation effort at this time.

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ABSTRACT

This final report under Contract NAS1-12043 summarizes a current NASA program to evaluate the utility of the OMEGA navigation system. With support from the Research Triangle Institute, NASA personnel at the Langley Research Center have initiated an experimental plan involving collection of a large volume of multifrequency OMEGA phase data. A literature search initiated studies to determine those parameters which most significantly affect OMEGA accuracies, particularly in the differential and composite modes. Founded on these studies and a genuine need for concentrated OMEGA phase data, a ground-based 12-18 month data gathering plan was designed and implemented in 1973. Receivers are being positioned at various locations throughout North Carolina, Virginia and Maryland. A computer simulation of the NASA-built digital phase-locked loop OMEGA receiver is used to characterize the receiver errors with and without measurement noise.

A theoretical formulation of differential and composite OMEGA error is presented to establish hypotheses about the functional relationships between various parameters and OMEGA navigational errors. Computer software developed to provide for extensive statistical analysis of the phase data is described. Several appendices are included to describe in detail the data handling software developed in this program. Provision has been made to incorporate specially-requested skywave corrections for each receiver site used.

Results from the regression analysis used to conduct parameter sensitivity studies on differential OMEGA error tend to validate the theoretically based hypothesis concerning the relationship between uncorrected differential OMEGA error and receiver separation range and azimuth. Limited results of measurement of receiver repeatability error and line of position measurement error are also presented. The results presented here and the capability described for future extensive analysis will provide information for design of OMEGA avionics and serve as a basis for evaluation of airborne receivers in typical operating modes. Recommendations are made concerning future planned flight test evaluation of a specific differential OMEGA receiver.

CHAPTER 1

INTRODUCTION

1.1 GENERAL

During the past two years, the NASA Langley Research Center at Hampton, Virginia, has been investigating the OMEGA navigation system. In the course of this study an experimental program was launched during 1973 by NASA personnel to create a large sample data base to provide for both concurrent and extensive future analysis of various OMEGA modes of operation. The ongoing experimental program, supported by the Research Triangle Institute under Contract NAS1-12043, involves collection of extensive three-frequency OMEGA phase data from all operational transmitters at various ground-based locations throughout Virginia, North Carolina and Maryland. Future efforts will be involved with completing the current data gathering plan and evaluating the utility of the OMEGA navigation system with emphasis on the differential and composite modes. Of particular interest is the applicability of OMEGA to aircraft navigational uses. Included are plans to use the final results of the current program in coordination with the FAA to design and implement an airborne test of a particular differential OMEGA hardware system developed under FAA contract.

Research Triangle Institute personnel have worked directly with NASA personnel in a coordinated team effort under the present contract. This contract final report, in an effort to provide a timely and comprehensive description of the program, serves to document many of the early results of this joint effort, including general descriptions of computer software and analysis results obtained at the Langley Research Center. More detailed descriptions are provided of the work performed by the Research Triangle Institute, which includes a background literature survey, theoretical analysis of differential and composite OMEGA error, a computer simulation evaluation of the NASA-developed digital phase-locked loop OMEGA receiver, and regression analysis of differential OMEGA error. Much of the detail of these supporting studies has been included in the appendices to this report.

A previous report (ref. 1) has described the operation of the OMEGA navigation system and investigated a very simple technique for providing OMEGA phase measurement corrections. The concepts of differential OMEGA and composite OMEGA were discussed as techniques which offer a means of extending the utility of OMEGA navigation and enhancing the achievable accuracy as compared to ordinary OMEGA. An initial investigation of the error sensitivity of these navigation modes was also reported. An extensive bibliography of published material relative to the OMEGA system appeared as an appendix.

The following sections of this chapter provide summaries of previous differential and composite OMEGA studies reported in the literature. From the perspective of these previous studies, some of the objectives of this current study are discussed in terms of data requirements.

1.2 Differential OMEGA

The concept of differential OMEGA was formally proposed in 1966 by the OMEGA Implementation Committee (ref. 2) with the implicit assumption that phase perturbation of a received signal within any small region will be highly correlated. The correlation is attributable to the signal transmitter to receiver propagation paths being essentially the same when the receiver region or differential region is small compared to the separation of this region from the transmitter(s). Generally the differential region is thought of as a circle of diameter 200-600 n.mi. (370.40-1111.20 km) centered on a "base receiver point." The measure of phase perturbations at the base receiver can then be used to correct any user receiver phase measurement within the differential region. The degree of correlation and how it varies throughout the differential region determines the degree to which the form of differential OMEGA can offer navigation accuracy improvement over ordinary OMEGA.

Previous differential OMEGA tests have indicated that navigational accuracies over ordinary OMEGA can be improved. Accuracies on the order of 0.25 n.mi. (.463 km) rms are quoted but delineation of the specific factors affecting this differential mode accuracy are not completely understood. Following is a discussion of what are considered to be the major previous differential OMEGA studies.

1.2.1 Tracor Ground Test.— As discussed in ref. 3, a ground-based differential OMEGA test was conducted for the U.S. Coast Guard with a base monitor receiver at Austin, Texas. User receiver sites were selected at ranges of from 50 to 300 n.mi. (92.60 to 555.60 km) on two azimuths, west and north, from the monitor receiver. Transmissions from Trinidad, Hawaii, and Forestport were monitored at 10.2 and 13.6 kHz during the fall of 1966. Phase readings, averaged over five minutes, were used to evaluate both "raw" differential OMEGA and skywave-corrected differential OMEGA. Results were obtained on all-daylight conditions, all-nighttime conditions, and for full 24-hour days. The daytime differential OMEGA rms errors were usually less than 0.25 n.mi. (.463 km) while nighttime errors occasionally exceeded one mile. Nighttime phase fluctuations were essentially uncorrelated for receiver separation ranges between 200-300 miles (370.40-555.60 km). Effects of anomalies such as the sudden ionospheric disturbances were essentially eliminated. The conclusion was made that differential OMEGA operation can eliminate prediction errors, transmitter synchronization errors and propagation variations including nighttime ionospheric variations and anomalous variations. Operation on a real-time basis was deemed cumbersome and expensive in that collection of monitor data for several days prior to a user operation served to be sufficient to eliminate prediction errors for a period of weeks. Synchronization accuracy was rationalized to be generally good and anomalies were relatively infrequent. The conclusion was also made that the use of short-term differential corrections at night for ranges greater than 50-100 miles (92.60-185.20 km) from a monitor station were likely to do more harm than good since variations appeared essentially uncorrelated. This particular test analysis was performed from the perspective of ship navigation requirements.

1.2.2 Tracor Airborne Test.— In ref. 4, some results are summarized from a series of OMEGA flight tests conducted jointly by the FAA, Navy and NASA. One objective was to determine the degree of navigation accuracy improvement differential OMEGA might offer over ordinary OMEGA. Time constants on the receivers were set to a nominal 30 sec, which was about half the value used in the test described above. Four lines of position (LOP) were monitored, AD, AC, BC and BD, at 10.2 kHz with phase readings logged at 5 min intervals and fixes obtained every 10 min using published skywave correction tables. A ground-based receiver was operated simultaneously on Bermuda and differential

corrections were obtained based on the chart LOP of this receiver. Radar tracking was provided using FPS-16 and FPQ-6 automatic tracking equipment to a range of approximately 100 mi (185.20 km) from Bermuda. No rate aiding was used in the aircraft which achieved speeds up to 200 knots (370.40 km/h). Conclusions drawn were that differential OMEGA does offer advantages over ordinary OMEGA. Nighttime non-skywave-corrected differential OMEGA showed an rms deviation of at most 0.65 n.mi. (1.20 km). A more precise estimate was not possible because various other system errors contributing to the test results could not be completely isolated.

1.2.3 Naval Research Laboratory Test.—References 5, 6, and 7 refer to a study of the accuracy of relative OMEGA which involved analysis of data collected during the Spring of 1969. Receiver separations of up to 40 n.mi. (74.08 km) were investigated with the base receiver at Waldorf, Maryland. The relative OMEGA error is the same as differential OMEGA error except for a constant which would be the difference in "true" value at the two receiver sites. Thus the standard deviation of the relative OMEGA error is a measure of the variation of the differential error. Absolute differential error cannot be obtained because this is a function of the "true" value chosen. Five minute averages of OMEGA phase data at 10.2 kHz were recorded over a period of generally 2-3 days at each mobile receiver site. Results showed that differential OMEGA was in fact relatively free from effects of anomalies which contributed to correlated transmitter-receiver path phase variations. Standard deviations of differential error were generally significantly better than 350 yd (315 m). It was concluded that receivers were a main contribution to relative error and a recommendation was made to conduct more extensive testing with improved receivers with a repeatability error of no more than 0.05 centicycle (cec).

1.2.4 Beukers Laboratories Test.—In the period January to April 1972 the Beukers Laboratories conducted a differential OMEGA test for the U.S. Coast Guard (refs. 8 and 9). Two monitor stations were set up, separated by 12 mi (22.22 km) on an east-west line, in New York state. A third receiver was positioned at eleven different sites varying in range up to 250 mi (463.0 km) north and 250 mi (463.0 km) west of the monitor stations. Phase data were recorded at 10 sec intervals from Hawaii, Trinidad, and Forestport on 13.6 kHz. Two primary objectives of this test were to determine phase

correlations at differential receivers for distant and near transmitters and to investigate time correlation of the phase variations. Receiver equipment repeatability tests indicated an rms tracking accuracy of approximately 1 cec.

It was concluded that for small separation of receiver equipment, the basic accuracy of differential OMEGA would not benefit from the use of skywave corrections. The need for skywave corrections is not evident until the stations are separated by a sufficient distance so that the diurnal timing difference is predominant.*

Mention was made of local effects problems encountered during the data gathering, which are valid considerations particularly with ground-based antennas. Power line interference was considered with actual measurement of line frequency variations near a rural distribution system. The point was made that a slight shift in the OMEGA frequencies could alleviate the interference problem.

The importance of using analog plots of the recorded phase data to guide the data analysis was emphasized. Often, phase perturbations can be recognized and identified rather easily using an analog plot (e.g., sudden ionospheric disturbances (SID), equipment outages) but can be very difficult to detect and classify using a machine algorithm on the digital data.

Night-to-night phase variations were larger than daytime fluctuations and did exceed ± 10 cec. The conclusion was made that skywave correction tables were not adequate if accuracy within ± 10 cec is desired for an LOP measurement.

Differential error was measured for east-west and north-south receiver separations and extended to other geographic areas on the basis of the error standard deviations and LOP crossing angles and phase gradients.

An attempt was made to correlate error with weather conditions, but the indication was that insufficient data were available during poor weather

*It should be noted that this conclusion is consistent with the argument that use of skywave corrections reduces dispersion error. Non-skywave-corrected differential OMEGA error during a transition period is in fact contingent on the timing difference of the diurnals between receivers. However, dispersion error is also related to the orientation of the receiver pair baseline to the transmitter pair LOP as is discussed in Chapter 2. Therefore, the improvement of differential error offered with the use of skywave corrections should not be evaluated solely on the basis of the receiver pair baseline orientation with respect to the sunrise-sunset line.

to provide conclusive results.

Time correlation studies were made, leading to the conclusion that differential error with the user receiver displaced west of the monitor receiver was reduced when corrections were delayed to compensate for the mean solar time difference between receivers. This effect was not noticed in other displacement directions. It was concluded that in general real time update is necessary for best overall accuracy.

In calculation of statistics, quarterly and full 24-hour mean values were used to determine standard deviations. The quarterly divisions provided analysis results for full daytime, nighttime, sunrise, and sunset periods. The 24-hour means were used to remove bias so that chart LOP values were never needed. Receiver repeatability error was determined to be approximately 1 cec (.07 n.mi. or .13 km). The statement was made that better receiver repeatability does not really improve precision since propagation variations are much larger (3-30 cec). This is with no skywave corrections.

1.2.5 Sercel Test.— Reference 10 discusses an evaluation test of a differential OMEGA system conducted in 1970. A series of tests including ground-based and ocean-based receivers was conducted on and off the coast of Western Europe using a correction receiver and various mobile receivers. Differential error was evaluated for receiver separations up to 400 n.mi. (740.80 km) and was found to increase as expected with separation distance. One minute samples at 10.2 kHz were used in analysis. Reference was made to antenna local effects problems including large structures near the antenna in the ground-based tests and also the effects of storm conditions. Signal-to-noise ratio presented a problem in the area of testing and one conclusion made was that the importance of correlation of noise at differential receivers to navigation accuracy decreases as signal-to-noise ratio increases. Time of day effect on differential error was also observed. The measured navigational accuracy was not as good as other tests have shown but projections were made indicating rms accuracies on the order of one-half mile or less should be obtainable out to 200-300 n.mi. (370.40-555.60 km) separation.

1.2.6 Naval Oceanographic Office Test.— Reference 11 describes a brief differential OMEGA test conducted in the Bahama Islands in the Fall of 1969 using a land-based monitor receiver and a shipboard mobile receiver with separations up to 140 n.mi. (259.28 km). Ten minute phase readings were

made at 10.2 kHz of B-C (Trinidad-Hawaii) and B-D (Trinidad-New York) LOP's. The Decca system with quoted accuracies of ± 0.1 n.mi. (.19 km) with a range of 150 n.mi. (277.80 km) from the monitor was used to determine the true position of the ship. Differential OMEGA error was evaluated as a 90% circular probability error and was found to be less than 0.80 n.mi. (1.48 km) out to a range of 150 n.mi. (277.80 km). Improvement of ordinary OMEGA accuracy was given as three to one. Little variation of error with receiver separation distance was observed. The ability of differential OMEGA to essentially eliminate the ordinary error due to a sudden ionospheric disturbance was observed.

1.2.7 Coastal Confluence Region Studies.— In ref. 12, the value of differential OMEGA as a navigational aid in the territorial waters of the Continental United States is discussed. This application is also a prime interest in earlier work (refs. 13, 14, and 15) involving differential OMEGA. Theoretical analysis of differential error, proposals of concepts for various telemetry equipment and some experimental testing are presented. In ref. 13, a test made in the vicinity of Monterey, California, in 1969 is discussed. Two differential separations of 17.7 and 40.2 n.mi. (32.78 and 74.45 km) were investigated. Calibration tests included operation with similar, separate antennas and use of a signal synthesizer. Line of position phase measurements of B-C and C-D were recorded at 10.2 and 13.6 kHz on strip chart recorders. Skywave corrections were obtained for the specific receiver sites used in the same temporal format of the published corrections so that linear interpolation was necessary to provide corrections for the ten-minute samples obtained from the data. The differential OMEGA concept was reported to improve overall navigation accuracy (24-hour period) by better than two to one. Improvement during local sunrise and sunset was on the order of five to one. Late afternoon conditions provided the least improvement over skywave-corrected ordinary OMEGA as the differential observations were relatively inaccurate and highly unstable. Once again the ability of differential OMEGA to overcome inaccuracies attributable to solar anomalies was evidenced. Generally, accuracy was improved with reduced receiver separation. Final conclusions indicated that even though the maximum differential error of 1.5 n.mi. (2.78 km) could be obtained and would be satisfactory in a harbor sea lane plan, better accuracies should be

obtainable with the concept. Reference 14 relates to implementation of a differential OMEGA system. Differential corrections are in the form of LOP adjustments to be transmitted to each user. LOP corrections are relative to chart lanes. A recommendation is made that inherent receiver error should be quantitatively described to insure good differential OMEGA accuracies. Reference 15 summarizes results of refs. 13 and 14.

In ref. 16 primary emphasis is given to phase error in a specific telemetry system for transmitting differential OMEGA correction information. The need for extended operational testing of differential OMEGA is specifically pointed out.

Use of differential OMEGA in the U.S. coastal confluence region is the primary interest expressed in ref. 12. The various factors which contribute to differential error are discussed. Those major sources are dispersion, modal interference, and statistical decorrelation errors. It is stated that in a system with skywave correction information, statistical decorrelation error may in fact become the limiting factor in differential OMEGA. Statistical decorrelation error does increase with receiver separation and functional forms for this have been investigated by Kasper in refs. 17 and 18. These functional forms for spatial correlation of the OMEGA signal were used to derive a functional form for rms position error relative to receiver separation distance. An rms error of less than 0.5 cec is predicted out to 200 n.mi. (370.40 km) from the base or monitor receiver. Based on this, differential OMEGA is suggested for application to airborne navigation with rms accuracies on the order of .2-.4 n.mi. (.37-.74 km).

Reference 12 also provides a summary of several previous differential OMEGA tests and related conclusions.

1.3 Composite OMEGA

The concept of composite OMEGA refers to utilization of more than one frequency of transmission in obtaining phase information for the navigation user. Fluctuations in the phase of the different OMEGA frequencies over a common propagation path are correlated, i.e., dispersive correlation, and are such that when properly combined, phase measurements are made and a resultant phase can be found which does not contain the large fluctuations which occur at any single frequency (refs. 19 and 20). Also, as discussed in the OMEGA Implementation Committee report (ref. 2), a

special case of composite OMEGA termed difference frequency OMEGA can provide a means of extending the lanes of unambiguous phase measurement to provide for lane identification when navigating with ordinary OMEGA or even differential OMEGA.

The interest in composite OMEGA is two-fold. It is of interest to know if difference frequency accuracy is sufficient to provide for lane identification needs on the one hand, and to evaluate the ability of the general concept of composite OMEGA as a means of providing sufficient navigation accuracy without a requirement for skywave corrections on the other hand.

In one study (ref. 21) analysis of the 3.4 kHz difference frequency phase (13.6 - 10.2 kHz) illustrates the need for more accurate predictions to provide for accurate difference frequency lane identification. Uncorrected difference frequency variations are generally reduced from those of either frequency alone (ref. 22) but better skywave corrections are needed to insure that the fluctuations of the difference frequency do not exceed the 50 cec required for lane identification at 10.2 kHz. In other studies (refs. 23 and 24) it is found that composite OMEGA, which involved linearly combining phase measurements of separate frequencies, could virtually eliminate the diurnal variations of the resultant phase. One of the main objectives of these studies was to point out the need for better skywave corrections at the 3.4 kHz difference frequency and to illustrate how these difference frequency corrections can be derived from the 10.2 kHz corrections. This relates directly to the lane identification use.

Use of composite OMEGA for aircraft navigation without need of skywave corrections is considered in ref. 24. Results indicate that composite accuracies are spatially varying so that perhaps some alternate skywave correction type information might be necessary to insure required precision.

In an NELC report (ref. 25) the conclusion is made that composite OMEGA offers no advantage in stability or accuracy over measurements at 13.6 kHz. It is further stated that the merit of composite OMEGA increases as the carrier stability decreases. This latter conclusion seems significant particularly in view of the fact that some evidence of modal interference has been observed at 13.6 kHz using the North Dakota signal which is at full power. More experimental evidence is needed to evaluate the abilities

of the composite mode.

In the NRL study (ref. 26) composite OMEGA illustrates an ability to greatly reduce navigation error due to signal phase fluctuations attributable to the polar cap absorption anomaly. These studies indicate that composite OMEGA as a means of navigation without the conventional skywave corrections may be feasible. It is particularly encouraging that phase anomalies which are not normally predictable can be suppressed through the use of composite OMEGA.

Results of the experimental program described in this report will be analyzed in composite form to more accurately define this concept as a means of lane identification for ordinary OMEGA and/or differential OMEGA. Particular emphasis is with respect to airborne navigation requirements.

1.4 Data Gathering Program Requirement

From the results of previous theoretical and experimental work as summarized in Section 1.2, the concept of differential OMEGA as a means of improving navigation accuracy is evident. Signal phase in a local region is in general highly correlated. This is perhaps best illustrated through the use of real time differential corrections to successfully eliminate the major error introduced by phase anomalies such as the SID (Sudden Ionospheric Disturbance) as observed in a number of tests. The need for real time differential corrections has been shown to be beneficial in at least one test (refs. 8 and 9). Various estimates of the accuracy which can be achieved have been made and range from approximately one-fourth mile to one mile. This represents a considerable improvement, in general, over ordinary OMEGA.

One of the primary motivations for the differential OMEGA use is to eliminate the need for skywave corrections which can be rather cumbersome for a navigator. A considerable effort is being made throughout the community of researchers to develop a very simple computerized system for automatically generating and incorporating a phase correction not only to simplify the use of corrections, but also to possibly improve the corrections. It is perhaps ironical that a large part of even differential OMEGA error contributed by dispersion can be eliminated by the use of skywave corrections (ref. 12). The conclusion is that without predicted skywave corrections

differential OMEGA is definitely superior to ordinary OMEGA. With skywave corrections the improvement offered by differential OMEGA is even more significant. In the absence of automated skywave corrections the question of how precise differential OMEGA can be on a consistent basis has to be adequately answered. Other considerations include operation in other modes such as difference frequency or composite OMEGA where phase information from multiple frequencies is used to eliminate the need for skywave corrections (ref. 19 for example). Sufficient data accumulated in a controlled experiment are needed to adequately evaluate the precision attainable with differential OMEGA specifically and also with composite OMEGA for a potential user. General results are needed which can be applied to the airborne user environment.

The current experimental program is designed primarily to answer some of these questions about differential OMEGA usage. In past studies, receiver repeatability has been an essential factor which has often not been adequately determined. Local effects problems encountered (particularly on land) when operating with a receiver antenna which is small compared to a VLF wavelength have received little attention. The primary factors which affect differential OMEGA accuracies are reasonably well understood but more adequate quantitative measures of the relative contribution of these factors are needed. For example, the extent to which statistical decorrelation error contributes to overall differential error has been theoretically discussed. It has not been generalized and analyzed to the extent that it can be predicted and related to other effects such as dispersion error and orientation of differentially operating receiver pairs with respect to the transmitter pair used. Time correlation of differential accuracy on a day-to-day basis as well as a season-to-season basis must be more adequately defined.

This report describes a currently-underway experimental plan designed to answer these and other questions related to differential OMEGA. Final analyses no doubt will depend on the accuracies attainable where all of the OMEGA transmitters are operational at full power. The current program has been limited in that respect but should provide useful results for the potential user. As stated, the primary goal of this investigation is the airborne user and the results of this experiment will provide a sound basis for design

of a series of flight tests to ultimately provide quantitative analysis of differential and composite OMEGA for aircraft navigation needs.

Chapter 2 presents a theoretically-oriented discussion of the parameters which affect the accuracy of differential OMEGA. The differential OMEGA error form is derived and the overall experimental test plan is presented. Chapter 3 discusses composite OMEGA, including difference frequency OMEGA which can be considered a special case of the composite mode. In Chapter 4, the OMEGA receiver equipment used in the experiment is described. Chapter 5 contains a discussion of the types of statistical analysis used to analyze the data. The data reformatting and editing procedures are also addressed. The regression analysis procedure is presented as a tool to provide assistance in parameter sensitivity studies. In Chapter 6, some preliminary data analysis results are presented, and Chapter 7 provides recommendations related to planned airborne tests. Ten appendices contain detailed derivations and discussions related to methods for data analysis and receiver equipment.

CHAPTER 2

DIFFERENTIAL OMEGA EXPERIMENTAL PLAN

2.1 General

The implicit assumption in differential OMEGA is that distance measurement errors are highly correlated within the immediate area of any given receiver site located in the usable range of the selected transmitters.

The assumption is certainly valid in view of the navigation accuracies attainable using ordinary OMEGA in conjunction with the published skywave correction tables where a given correction applies over a relatively large area of operation. However, the question of exactly how much improvement in navigation accuracy can be attained by using the differential mode of operation has not been adequately quantified.

To determine the errors in position measurements using the differential mode under a given set of conditions, it is necessary to delineate the factors that are expected to affect the errors in phase measurement and to estimate the effect of these factors on the position measurement accuracy. Through previous tests of the differential OMEGA concept and from analysis of the physics of VLF propagation it is possible to delineate various factors or parameters which might contribute to the variation of errors in phase measurements within the immediate locale of any given OMEGA receiver site. Some of these parameters are more significant than others and many are not statistically independent. It also seems apparent that additional parameters may be significant for a situation involving airborne receivers instead of ground based receivers. Although the airborne utility of differential OMEGA is the ultimate goal, the initial experimental program involves ground-based receivers only.

Table 2-1 provides a list of the parameters to be considered. The most important of these are believed to be range between receiver locations, time of day, orientation of direction of line-of-sight between receiver locations, and seasonal variations. The others are felt to be important to a lesser

TABLE 2-1. Differential OMEGA Parameters of Interest

-
- A. Distance between base receiver and mobile receiver.
 - B. Time of Day: (1) Relative time at each receiver.
(2) Time during day relative to day/night conditions.
 - C. Orientation of base-mobile receiver line-of-sight (l.o.s.) with respect to Line of Position.
 - D. Orientation of base-mobile receiver l.o.s. with respect to earth's magnetic field.
 - E. Receiver Time Constant
 - F. Receiver System Error.
 - G. OMEGA Frequency
 - H. Season of Year
 - I. Weather Conditions
 - J. Modal Interference
-

degree. The data analysis will be designed to determine which are in fact the most significant parameters.

In selecting the parameters of interest an analysis of the skywave corrections taken from the published tables has proven useful. Plots provided in ref. 1 illustrate the type of analysis conducted. Isolines of phase difference corrections are plotted for several different transmitter pairs usable in and around North America. These plots illustrate that range, azimuth and time are highly significant parameters in the variation of phase measurement corrections over large areas. It would therefore be expected that these parameters are also significant within a small localized area.

The goal of the experimental program is to determine how each of these parameters affect differential OMEGA accuracy and, if possible, to develop prediction equations applicable for this mode. The following sections contain an analytical discussion of the differential OMEGA error form and a description of the experimental plan designed to provide parameter variations over a wide range of interest.

2.2 Differential OMEGA Error Form

The differential OMEGA concept as previously mentioned may be viewed as a mode whereby skywave corrections are measured in real time. This would provide a means of navigation independent of predicted skywave corrections. It is shown that a large part of the differential error can be eliminated with good predictions of skywave corrections.

2.2.1 Non-skywave-corrected differential OMEGA.— In the non-skywave-corrected mode of operation, differential OMEGA can be represented in terms of a fixed site base receiver and a "user" operating in the differential region without the aid of any predicted skywave corrections. For purposes of this analysis differential error will be defined as that error incurred at the "user" receiver position in estimating the true line-of-position (LOP). The true LOP will be assumed to be the chart LOP based on a nominal phase velocity, $(c/.9974)$, as used in published charts. Later in this analysis consideration will be given to other definitions of true LOP and the associated effect on differential error.

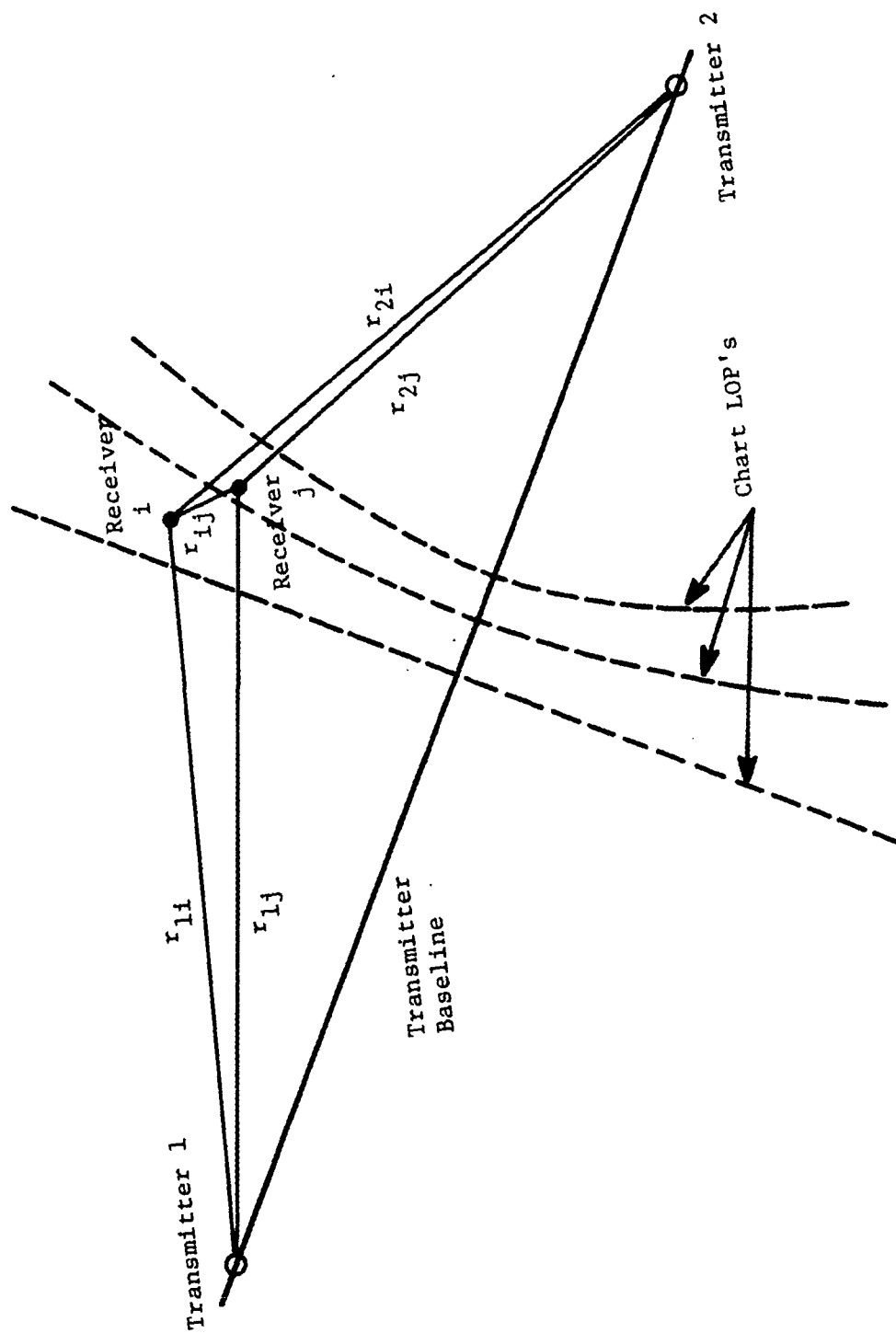


Fig. 2-1. Two receivers located in a differential region between two OMEGA transmitters.

Consider the differential OMEGA situation given in Figure 2-1. Receiver 1 represents the base station receiver in some arbitrarily chosen differential region between two OMEGA transmitters labelled 1 and 2. The differential OMEGA user receiver j will have a differential navigation error defined as the difference in the chart value at the receiver position j and the differentially corrected measurement of LOP_{1-2} at receiver j. Strictly speaking this is a correction term, i.e., a term to be added to the differentially corrected measurement to yield the chart estimate equal to the true chart value. The differential correction as measured at receiver 1 (base receiver) is

$$\delta\phi_{\text{corr}}(1) = \phi_c(1) - \phi_{\text{meas}}(1) \quad (2-1)$$

where $\phi_c(1)$ is the charted LOP_{1-2} phase difference and $\phi_{\text{meas}}(1)$ is the measured LOP phase difference both taken at receiver 1. The differential error, $\epsilon_D(j)$, at receiver j is then

$$\epsilon_D(j) = \phi_c(j) - [\phi_{\text{meas}}(j) + \delta\phi_{\text{corr}}(1)] \quad (2-2)$$

which can be expanded using (2-1) to yield

$$\epsilon_D(j) = [\phi_{\text{meas}}(1) - \phi_{\text{meas}}(j)] - [\phi_c(1) - \phi_c(j)] \quad (2-3)$$

Using the distances in Figure 2-1 the differential error in (2-3) can be written as

$$\epsilon_D(j) = 100 \left[\left(\frac{r_{11}}{\lambda_{11}} - \frac{r_{21}}{\lambda_{21}} \right) - \left(\frac{r_{1j}}{\lambda_{1j}} - \frac{r_{2j}}{\lambda_{2j}} \right) \right] - \left[\left(\frac{r_{11}}{\lambda_c} - \frac{r_{21}}{\lambda_c} \right) - \left(\frac{r_{1j}}{\lambda_c} - \frac{r_{2j}}{\lambda_c} \right) \right] \quad (2-4)$$

where the phase of the OMEGA signal from transmitter K at receiver i is expressed in terms of the distance r_{Ki} and an associated path wavelength λ_{Ki} . The factor 100 appears in (2-4) such that $\epsilon_D(j)$ is in centicycles at the particular frequency of operation.

Define a new variable η_{Ki} where

$$\eta_{Ki} = \frac{\lambda_c}{\lambda_{Ki}}$$

is the relative wavelength over a given propagation path which may be considered a random variable with mean $\bar{\eta}_{Ki}$ and standard deviation $\sigma_{\eta_{Ki}}^2$. Therefore (2-4) becomes

$$\epsilon_D(j) = \frac{100}{\lambda_c} \left\{ r_{1i}(\eta_{1i} - 1) - r_{2i}(\eta_{2i} - 1) - r_{1j}(\eta_{1j} - 1) + r_{2j}(\eta_{2j} - 1) \right\}. \quad (2-5)$$

Using differential OMEGA the range between receivers within the differential area is much smaller than the range between any receiver and the transmitters so that $r_{ij} \ll r_{1j}, r_{2j}, r_{1i},$ or r_{2i} . This is the basis for the definition of the differential OMEGA region and the associated assumption that propagation along paths r_{1i} and r_{1j} is highly correlated as is propagation along paths r_{2i} and r_{2j} . Therefore the error defined in (2-5) is made up of the error resulting from decorrelation along the adjacent transmitter-receiver paths as well as the error resulting from different path lengths even though propagation is correlated. The error assuming correlated propagation can be found from (2-5) with $\eta_{1i} = \eta_{1j}$ and $\eta_{2i} = \eta_{2j}$.^{*} The total error allowing for some path decorrelation is then

$$\epsilon_D(j) = \frac{100}{\lambda_c} \left\{ (\eta_1 - 1)(r_{1i} - r_{1j}) - (\eta_2 - 1)(r_{2i} - r_{2j}) \right\} + \epsilon'_D(j) \quad (2-6)$$

where $\epsilon'_D(j)$ is the statistical decorrelation error discussed in ref. 12 and attributed primarily to ionization irregularities. This error would also be a function of any delay between the time the base receiver measures a correction and the time the "user" receiver applies this correction. It in

^{*}This assumption is not valid during the total transition period when the two receivers are not located on the sunrise-sunset line. This is evidenced by the results of the Beukers Labs report (ref. 8) showing that differing daylight conditions can have an effect within a differential OMEGA area.

turn should be independent of the definition of the true value used to determine differential error. Statistical decorrelation error can be determined from experiment. In ref. 27 two statistical models were used to derive two different spatial correlation functions. These can be used to get a measure of spatial decorrelation error; however, these are expressed only as a function of range separation and do not provide functionally for different orientations of the base-user receiver baseline. (See Appendix A.) If the receivers are displaced along an LOP the decorrelation error should be larger for a given range separation than for displacement along the perpendicular to an LOP.

The bracketed term in the expression for differential error in (2-6) is classified in ref. 12 as a geometric divergence error or a generalized dispersion error. This error is a consequence of the actual average phase velocity along the transmitter-receiver paths being different from the chart value or any other "true value" which might be used to define the differential error. Thus the diurnal phase velocity change essentially determines the range of the dispersion error.

As a simple example consider an exaggeration of the phenomenon as depicted in Figure 2-2. The daytime lane, nighttime lane and chart lane are all different with the nighttime lane somewhat smaller than the chart lane and the daytime lane larger than the chart lane. The base receiver has a chart phase of 52 cec, a daytime phase of 23 cec and a nighttime phase of 87 cec. The user receiver has a chart phase of 38 cec, a daytime phase of 3 cec and a nighttime phase of 87 cec. The phase difference between the two receivers is 14 cec on the chart, 20 cec during the day, and 0 cec at night. This is with no decorrelation error or receiver error and discounting any modal interference. It can be noted from the example that good skywave correction data can virtually eliminate the errors due to dispersion. This will be discussed in the next section. It can also be seen from this example that by using chart position as true position, daytime dispersion error is less than nighttime dispersion error. In reality it is even more severe than illustrated here since the daytime lane is much more nearly the same as the chart lane than is the nighttime lane. To minimize the maximum dispersion from true value occurring over a 24-hour period the median phase velocity between the daytime and nighttime excursions could be used as is suggested in ref. 12.

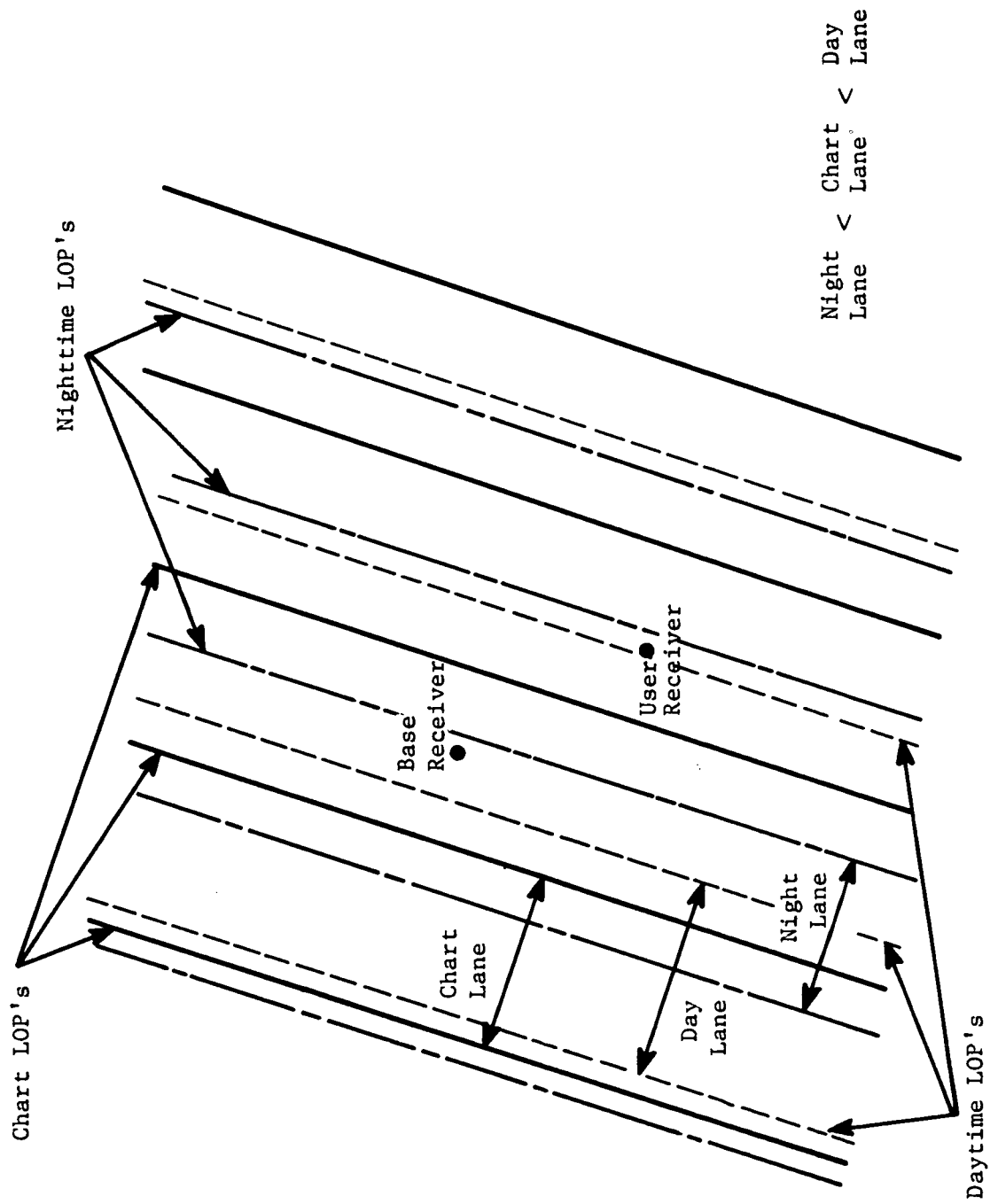


Fig. 2-2. Illustration of dispersion due to variation in phase velocity.

Another source of "generalized dispersion" error is modal interference. This contributes to irregularities in the lane structure in that phase predictions cannot be made in terms of an average phase velocity or average wavelength. The wavelength is in effect spatially varying. An analysis summary in ref. 12 illustrates how modal interference can contribute to differential error. No time variation in this error is alluded to; however, data gathered by NASA Langley during the period September 1973 to March 1974 indicate that time variations, particularly at night, can be significant.

Rewriting (2-6), the differential error can be expressed as

$$\epsilon_D(j) = \frac{100}{\lambda_c} \left\{ (1 - \eta_2) \left[(r_{1i} - r_{2i}) - (r_{1j} - r_{2j}) \right] + (\eta_2 - \eta_1)(r_{1i} - r_{1j}) \right\} + \epsilon'_D(j) \quad (2-7)$$

where the first term inside the braces is the contribution to dispersion error assuming the phase velocity over path 1 is the same as over path 2. The second term accounts for differences in the path phase velocities. This expression can be simplified by noting that

$$\frac{(r_{1i} - r_{2i}) - (r_{1j} - r_{2j})}{\lambda_c} .100$$

is the chart difference in LOP phase at the two receivers and can be expressed as a function of the chart LOP phase gradient at the base receiver $\Delta\phi_c(i)$, the range separation between receivers r_{ij} , and the angle between the receiver baseline and the LOP phase gradient. This is illustrated in Figure 2-3.

Furthermore, the difference $\frac{(r_{1i} - r_{1j})}{\lambda_c} .100$ represents the difference in chart phase of the transmitter 1 signal at receivers i and j. It can be expressed approximately in terms of the magnitude and azimuth of a transmitter 1 phase gradient at receiver i, the range between receivers, and the orientation of the baseline between receivers. Figure 2-4 illustrates this relation.

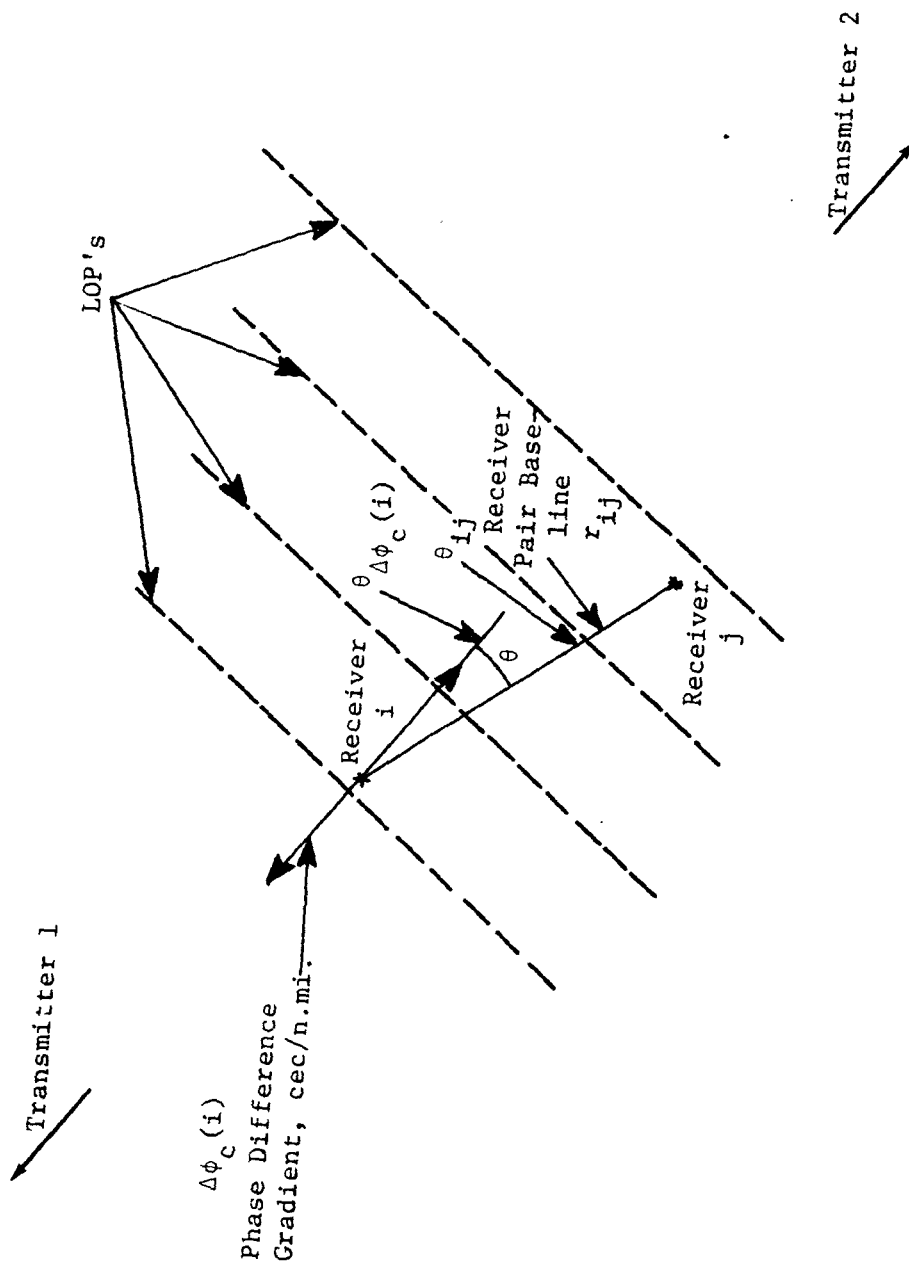


Fig. 2-3. Geometry of receiver pair baseline with respect to lines of position.

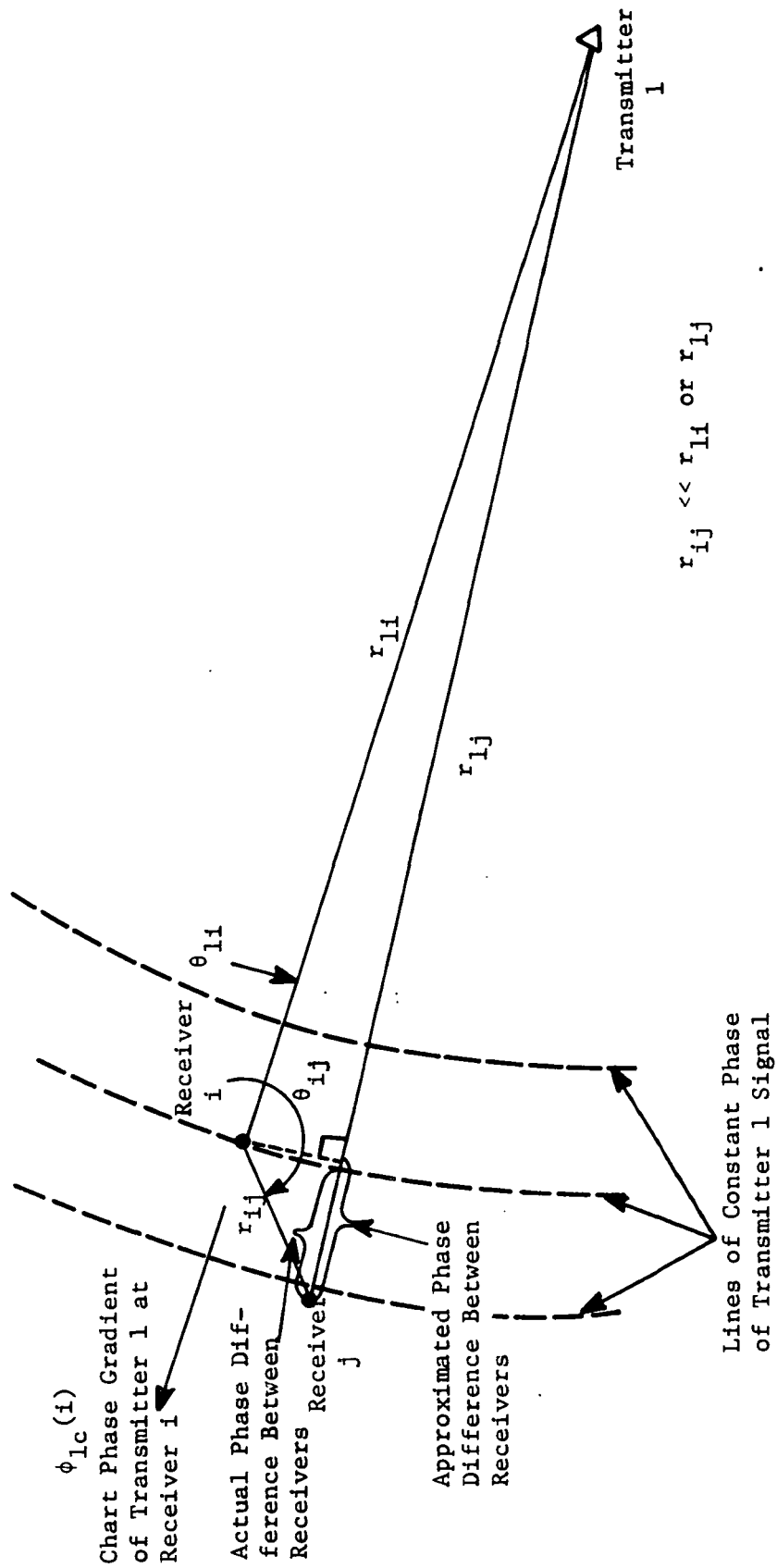


Fig. 2-4. Geometry of receiver pair baseline with respect to phase gradient of Transmitter 1 signal.

Thus (2-7) can be rewritten as

$$\begin{aligned} \epsilon_D(j) = & (1 - \eta_2) \Delta\phi_c(i) r_{ij} \cos(\theta_{\Delta\phi_c}(i) - \theta_{ij}) \\ & + (\eta_2 - \eta_1) \phi_{1c}(i) r_{ij} \cos(\theta_{1i} - \theta_{ij}) + \epsilon'_D(j) \end{aligned} \quad (2-8)$$

where

$\Delta\phi_c(i)$ = chart LOP phase gradient at receiver i,

r_{ij} = range separation between base receiver i and user receiver j,

$\theta_{\Delta\phi_c}(i)$ = angle of chart LOP phase gradient at receiver i relative to true north,

θ_{ij} = angle of receiver i-j baseline relative to true north,

$\phi_{1c}(i)$ = chart phase gradient of transmitter 1 at receiver i (a constant for a given base receiver site),

θ_{1i} = angle of radial from transmitter 1 to receiver i measured at receiver i relative to true north,

$\epsilon'_D(j)$ = statistical decorrelation error,

η_k = relative wavelength of OMEGA signal over path from transmitter k to differential area of interest.

Other factors can contribute to differential OMEGA phase error. For example the effects of earth magnetic field on VLF propagation can be accounted for in terms of the value of η_1 and η_2 included in (2-8). These may have independently determined values depending on the directions of propagation relative to E-W from each transmitter to the differential area of operation.

Other independent error sources can be considered separately. These include local receiver antenna environment effects and inherent receiver system errors (See Section 2.2.3). Time correlation effects can also be included and have been discussed in refs. 8 and 12. Off-path propagation effects are also mentioned in ref. 12.

2.2.2 Skywave-corrected differential OMEGA.—The basic form of differential OMEGA does not change with the application of skywave correction information. However, the achievable precision which can be attained is improved with good skywave corrections. An obvious criterion for corrections to be useful is that they not be the same for base and mobile receivers. Otherwise no change from the non-skywave corrected mode exists. This would mean that the currently published correction tables would be of limited value since the grids used are generally the same area size as an average differential region. More detailed skywave corrections could serve to reduce dispersion error. This could include predictable error resulting from modal interference.

To see how skywave corrections can reduce dispersion error it is only necessary to recall basic definitions. The skywave correction at a particular receiver location is generally the phase value to be added to the phase measurement to "correct" it to the chart value. The difference between two corrected measurements at two different receiver locations then becomes the difference between chart values. Thus, real time corrections would reduce the phase difference between two differential receiver measurements to that resulting from other than dispersion error. Non-real time or average skywave corrections can serve to reduce dispersion error with the reduction proportional to the quality and timeliness of the corrections.

As stated in ref. 9, the error due to dispersion is small for small receiver separation ranges. Thus the extent to which skywave corrections can significantly improve navigational accuracy is limited by the magnitude of the statistical decorrelation error and inherent receiver equipment error. Generally for receiver separations of less than 50 n.mi. (92.60 km) dispersion error should be less than that due to other sources.

The extent to which skywave corrections reduce modal interference related error depends considerably upon the extent to which this interference is spatially dependent. Time changes in modal interference will most likely be accounted for by skywave corrections only on a gross scale.

By reducing the differential OMEGA error, skywave corrections also make feasible the utilization of larger differential areas under the constraint of a given allowable navigation error. This could be particularly attractive because it affords a reduction of required base stations while providing a navigational capability for some large area equipment.

2.2.3 Local receiver error contribution.— Some portion of differential OMEGA error is attributable to what is termed "local effects." This error is the result of phase perturbations relative to physical placement of the antenna, orientation of the antenna, power line interference, local terrain and vegetation, local weather conditions, etc. Generally these are uncorrelated errors in the differential mode since local effects at one receiver will generally be independent of those at another receiver. One of the major needs is to evaluate the contribution to error from local effects. This problem has received virtually no attention in the literature. For land based receivers the problem of power line interference has been noted (ref. 9) with major emphasis given to recommended selection of new OMEGA frequencies to circumvent the identified problem.

In the preliminary stages of data gathering of OMEGA phase readings using land based receivers in this experiment the effects of local terrain and vegetation have proved significant. For example, when using a whip antenna to receive the OMEGA signal, many trees are better "antennas" than the whip so that re-radiated interference can be a problem. It has been observed that antennas near the ground located in terrain depressions can experience a severe reduction in signal strength as opposed to antennas located on locally higher ground. Orientation has not been found to be significant.

Effects of power line interference have been intermittent. These seem to vary at a given receiver site from week to week. No specific correlation with local temperature and humidity conditions nor load conditions on the power lines has been made thus far.

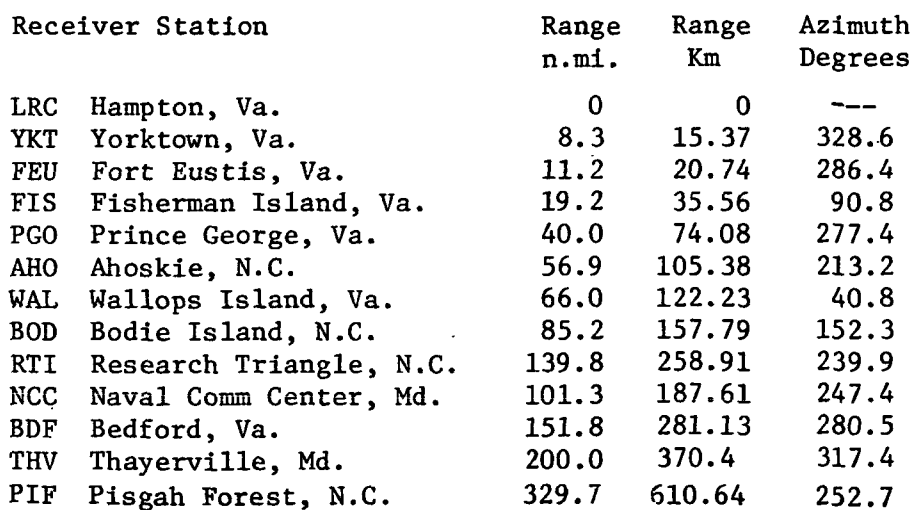
The primary emphasis in designing the experimental phase has been on eliminating differences in local effects and avoiding uncorrelated perturbation conditions. Data which are found to be contaminated with 60 Hz power line interference have been largely disregarded when analysis of other error contributions is made. Antenna placement has been essentially restricted to forest fire observation towers, roofs of buildings, and open terrain in an attempt to avoid multipath problems. Power lines have been avoided where possible.

Any large conductor placed near a small whip antenna can have an effect on the received phase at the whip antenna due to re-radiation. Some analytical analysis work has been carried out at the Langley Research Center in an attempt to quantify this effect. Results are not presented here; however, Appendix B is included to illustrate how the earth's conductivity affects the orientation of the electric field at the earth's surface.

2.3 Experimental Design Plan

The experimental design plan presented is a function of the analysis techniques used as well as the goals of the experiment. The philosophy of design is that the plan be adaptive in the sense that exact site location, revisit times, etc., can be altered as the data analysis progresses so as to minimize uncertainties in parameter sensitivities.

Two receivers will be positioned to record OMEGA phase data simultaneously during the times when data are accumulated. A planned period of from 14 to 18 months was initiated in September 1973. One receiver, located at the Langley Research Center (LRC), Hampton, Virginia, will remain as a permanent station throughout the program and is termed the "base receiver." An identical receiver, in a mobile trailer, is being moved to various selected sites throughout a region defined by a circle of radius approximately 300 n.mi. (555.60 km) centered at Hampton. A minimum of 12 sites (in addition to the base receiver site) has been chosen at various ranges and azimuths from the base site throughout this test region. Each



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site will be visited at least twice for a period of approximately 72-120 hours. Periods between same-site visits will be varied from one month to approximately 12 months. Additional sites will be selected during the course of the experiment as deemed necessary from the data analysis.

The primary criterion used to select the set of sites shown in Figure 2-5, to specify additional sites, and to determine the site re-visitation schedule and the duration of each visit is based on the need to improve confidence in parameter sensitivity analysis results of differential OMEGA. Enough data points are needed to cover the range of interested separations between receivers, mobile-base receiver station line-of-sight azimuths and short- and long-term temporal effects and other parameters which affect differential OMEGA accuracy. For example, the functional relationship between accuracy and receiver separation range is believed to be more significant within 100 n.mi. (185.20 km) than beyond so that more mobile receiver sites have been selected within 100 n.mi. (185.20 km) of the Hampton base receiver than beyond. A histogram plot of selected ranges and azimuths relative to Hampton, Virginia, is shown in Figure 2-6. The azimuth of the B-D (Trinidad-North Dakota), A-C (Norway-Hawaii), and B-C (Trinidad-Hawaii) lines of position (LOP) at Hampton are indicated on the azimuth histogram. Table 2-2 provides a summary of the site visitation schedule for the mobile receiver. The side-by-side operation periods are not included but are interspersed so that adequate determination of receiver repeatability error is provided.

In Section 2.2.2 dispersion error was found to be related to $R\cos\theta'$ where θ' is the azimuth from base receiver to mobile receiver relative to the perpendicular to a selected LOP and R is the receiver separation range. Figure 2-7 provides histograms for the $R\cos\theta'$ values for the LOP pairs A-C and B-D using the sites given in Figure 2-5. To improve confidence in analysis results, if the $R\cos\theta'$ variation is valid, prime candidates for additional sites would be those for which the $R\cos\theta'$ values are interspersed between those values shown in Figure 2-7.

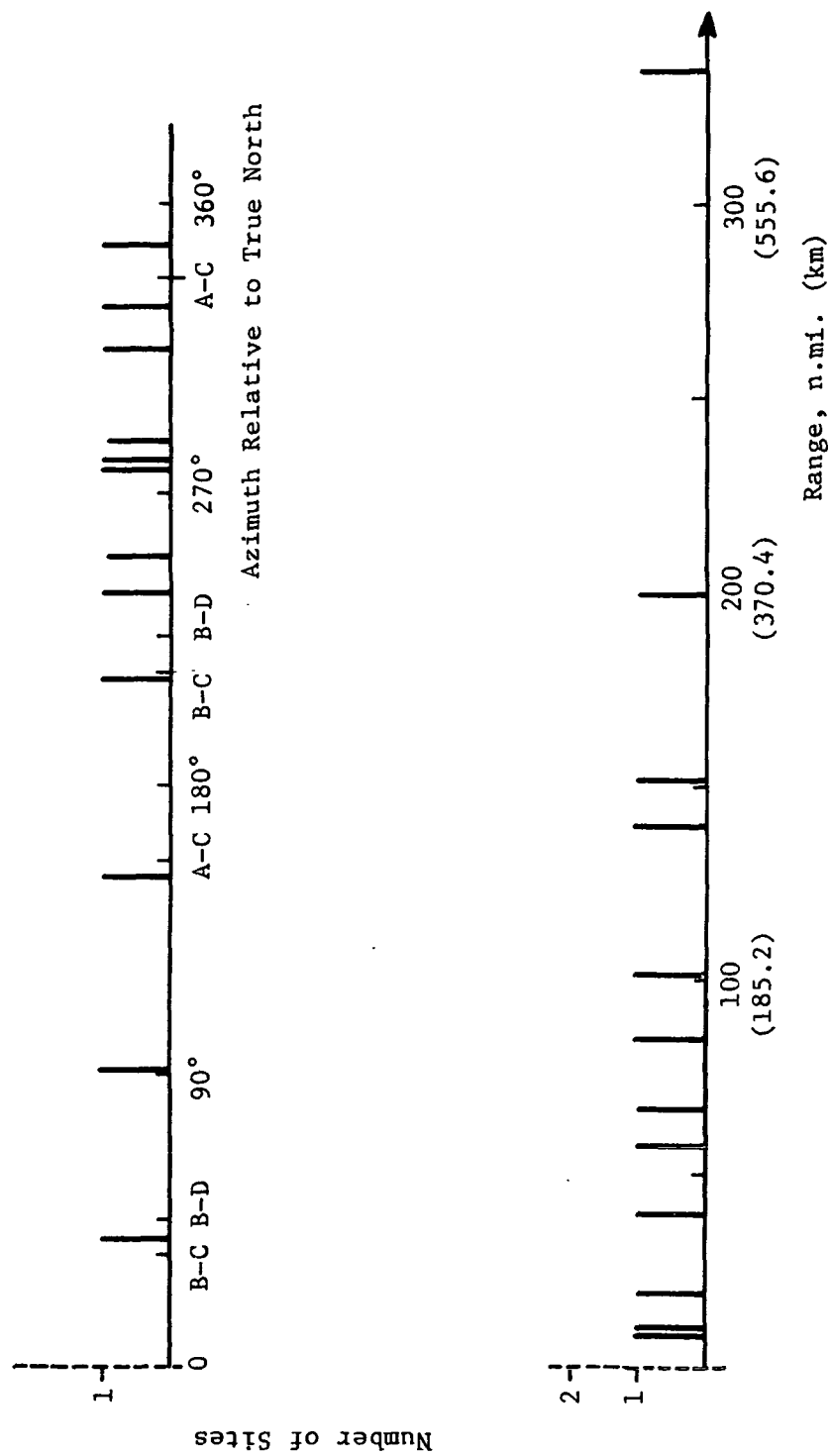


Fig. 2-6. Histograms of range and azimuth from Hampton, Va., base receiver to selected mobile receiver sites.

LOCATION	1973												1974												1975
	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan							
Yorktown, Va.																									
Fort Eustis, Va.																									
Fisherman Island, Va.																									
Prince George, Va.																									
Ahoskie, N.C.																									
Wallops Island, Va.																									
Bodie Island, N.C.																									
Cheltenham, Md.																									
Research Triangle, N.C.																									
Bedford, Va.																									
Thayerville, Md.																									
Rosman, N.C.																									

Table 2-2. Mobile receiver site visitation schedule.

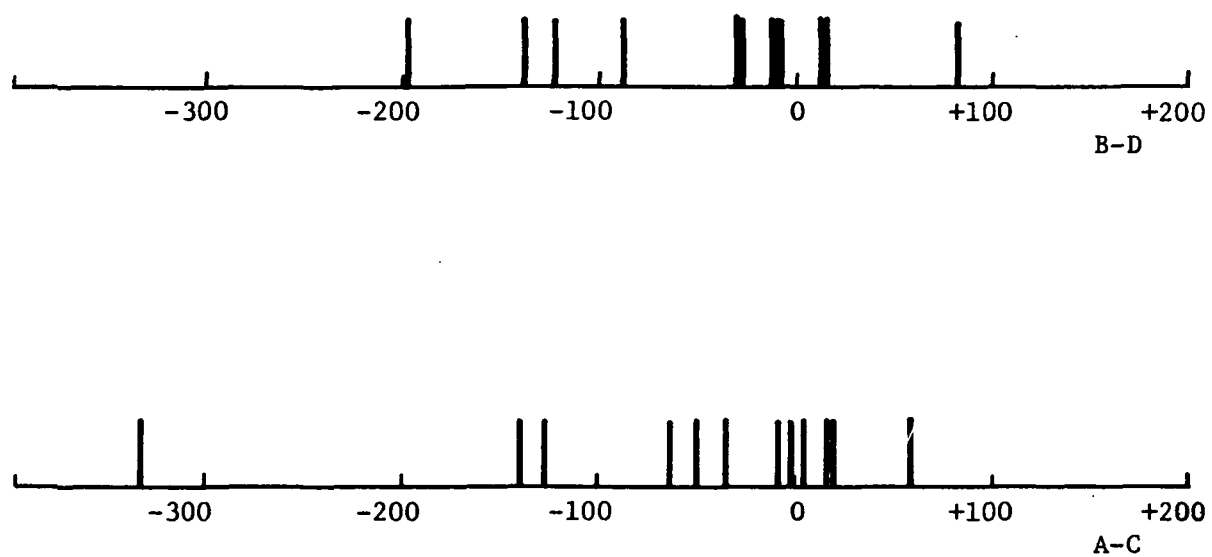


Fig. 2-7. Histogram of $R\cos\theta'$ differential dispersion error variable for LOP pairs A-C and B-D.

2.3.1 Recorded data.— Each receiver station has the capability of recording relative phase data from the stations A, B, C, and D at all three OMEGA frequencies (10.2, 11 1/3, and 13.6 kHz) simultaneously. Ten second phase measurement samples will be recorded on digital tape along with time of day and selected signal strength measurements. Each receiver station includes a TRACOR 599R receiver capable of receiving four transmitted signals simultaneously at a given frequency with frequency selection determined by the operator. Provision is made for strip chart recordings of signal amplitude of three channels on the selected frequency. The time constant of the TRACOR receiver is approximately 10 sec. A second receiver designed and built by NASA is a digital phase locked loop receiver with twelve loops such that relative phase measurement of four transmitted signals at all three OMEGA frequencies can be output at 10 sec intervals. Initially the loops in this receiver were modified second order loops but were changed to first order loops during the course of the program. A complete discussion of the receivers with associated phase measurement capability is provided in Chapter 4 and Appendix D.

Phase data from the two receiver equipments are commutated and fed to the input of a Kennedy Model 1600R incremental digital tape recorder. Measured phase is recorded in terms of digital clock counts so that relative phase measurement accuracy is ± 0.25 cec, ± 0.28 cec, and ± 0.33 cec at 10.2 kHz, 11 1/3 kHz, and 13.6 kHz at the particular frequency of interest. Appendix D provides more detailed analysis of the recorded information.

At each receiver site the latitude and longitude are recorded and during data gathering periods a weather log is maintained along with information concerning the selected TRACOR frequency and any unusual signal conditions noted. The mobile receiver is normally not attended during a particular three to five day period, and NOAA weather summaries are used to obtain local weather conditions for much of the data. Ionospheric disturbance data will be obtained during the analysis phase to provide sunspot activity information.

2.3.2 Mobile receiver site selection.— Based on some preliminary measurements, site selection for the mobile receiver complex will be made so that local effects as discussed in Section 2.3.3 will be correlated.

This should result in data which are relatively independent of uncorrelated perturbations which might be attributed to the local receiver conditions.

Generally sites are selected so that the antennas can be located as high above the ground as possible. When possible, forest fire observation towers or building roofs are used. Otherwise areas clear of trees and other large conductors on high ground are used. Positions are selected near survey markers which are included in the U.S. Coast and Geodetic Survey charts or state survey charts. Many of these points have latitude and longitude recorded to the nearest ten-thousandth of a second. In any event, survey accuracies of antennas should be within ± 50 feet (15.24 m). Provision for obtaining height above sea level has not been made and all ground distances are calculated at sea level. Appendix C provides a detailed analysis of the method used for calculation of geodetic distances and azimuths.

2.4 Summary

The experimental plan which has been outlined is designed to provide data for a comprehensive analysis of differential OMEGA in a ground-based environment. The results can yield a quantitative measure of navigation errors in the Hampton, Virginia, differential region and should provide some general conclusions concerning the sensitivity of navigational accuracy to various parameters. The regression techniques for parameter sensitivity studies will be discussed in Chapter 5.

In that these data will be so comprehensive and collected over such an extended period of time, useful results on ordinary OMEGA and particularly composite OMEGA can be obtained. Special skywave corrections are being obtained from the Hydrographic Center of the Defense Mapping Agency for the particular receiver site locations used for the times during which data are gathered. These will afford an opportunity to evaluate the precision of these corrections. Emphasis will be placed on comparison of non-skywave correction modes of OMEGA and skywave corrected ordinary OMEGA. Also correction evaluations at 11 1/3 kHz will be unique since these have not previously been used.

CHAPTER 3

COMPOSITE OMEGA

3.1 General

As mentioned previously the term "composite OMEGA" will be used in this report in a general sense to include what is referred to as difference frequency OMEGA. Composite OMEGA has been defined for at least two purposes in an operational sense. Difference frequency OMEGA is designed to be used in conjunction with ordinary OMEGA as a means of lane resolution. This provides for the extension of the region of unambiguous phase measurement on the ground from approximately 6 n.mi. (11.11 km) for 13.6 kHz LOP measurements to approximately 72 n.mi. (133.34 km) for the 1.1 1/3 kHz difference frequency LOP measurements. For lane identification purposes it is conceivable that operation without skywave corrections can provide sufficient accuracy. This is particularly desirable since other investigators have found difference frequency published skywave corrections to be rather poor (refs. 21, 23, and 24). The data obtained during this program will be used to evaluate the capability of lane identification without skywave corrections.

A second capability of composite OMEGA is to provide for a signal phase which exhibits small variations relatively independent of diurnal effects. The data obtained in the current program will be used to provide comparisons with previous results (refs. 23 and 24) and a quantitative analysis of the utility of composite OMEGA.

3.2 Composite OMEGA Phase

Composite OMEGA involves obtaining some resultant signal which has a phase commonly expressed as a linear combination of phases of two or more fundamental OMEGA frequencies. Let ϕ_{comp} designate this composite phase. If the component OMEGA phases are expressed as phase measurements from one OMEGA transmitter then ϕ_{comp} will be a composite phase measurement from a single transmitter. If the component phases are LOP phase differences then ϕ_{comp} is a composite LOP phase difference between two OMEGA transmitters. The meaning of ϕ_{comp} should be clear within the context of the discussion that follows. In general, at some time t the composite phase in units of cec at 10.2 kHz can be expressed as

$$\phi_{\text{comp}}(t) = a_0 + a_1 \phi_{10.2}(t) + a_2 \left[\frac{9}{10} \phi_{11.3}(t) \right] + a_3 \left[\frac{3}{4} \phi_{13.6}(t) \right] \quad (3-1)$$

where $\phi_{10.2}(t)$, $\phi_{11.3}(t)$, and $\phi_{13.6}(t)$ are phase differences in cec at the respective frequency. The a_i are variables which may be spatially dependent, i.e., $a_i = a_i(x,y)$, and are generally specified based on some defined criterion. For example if $a_2 = a_0 = 0$, $a_1 = 3$, and $a_3 = 4$ then (3-1) becomes

$$\phi_{\text{comp}}(t) = 3\phi_{13.6} - 3\phi_{10.2} = 3\phi_{3.4}(t) \quad (3-2)$$

where $\phi_{\text{comp}}(t)$ is the phase of the 3.4 kHz difference frequency in cec at 10.2 kHz. If (3-2) were used to obtain LOP position in a given 3.4 kHz lane to subsequently determine the 10.2 kHz lane in which the navigator is located, then the error in $\phi_{\text{comp}}(t)$ must be within ± 50 cec at 10.2 kHz or within $\pm \frac{50}{3}$ cec at 3.4 kHz. (Note $\phi_{13.6}$ and $\phi_{10.2}$ would be LOP phase measurements for $\phi_{\text{comp}}(t)$ to be an LOP phase.)

As another example consider $a_0 = a_3 = 0$ and $a_1 = -9$, $a_2 = 10$. Then (3-1) yields

$$\phi_{\text{comp}}(t) = 9[\phi_{11.3}(t) - \phi_{10.2}(t)] = 9 \phi_{1.1 \frac{1}{3}}(t) \quad (3-3)$$

where $\phi_{\text{comp}}(t)$ is the phase of the 1.1 1/3 kHz difference frequency in cec at 10.2 kHz. If (3-3) were used to obtain LOP position in a given 1.1 1/3 kHz lane to subsequently determine the correct 10.2 kHz lane in which the navigator is located then the error in $\phi_{\text{comp}}(t)$ must be within ± 50 cec at 10.2 kHz or within $\pm \frac{50}{9}$ cec at 1.1 1/3 kHz. Note that if $\phi_{\text{comp}}(t)$ is expressed in cec at 3.4 kHz then

$$\phi_{\text{comp}}(t) = 3 \phi_{1.1 \frac{1}{3}}(t)$$

such that the correct 3.4 kHz lane could be identified if $\phi_{\text{comp}}(t)$ is within ± 50 cec at 3.4 kHz or within $\pm \frac{50}{3}$ cec at 1.1 1/3 kHz. Subsequently the correct 10.2 kHz lane could be identified using (3-2) if the 3.4 kHz LOP phase can be measured within $\pm \frac{50}{3}$ cec at 3.4 kHz. Thus the 10.2 kHz lane can be identified by going directly from the 11.3 kHz and the 10.2 kHz phases

or by using all the OMEGA frequency phases and using a two-step procedure. This exemplifies the ability of difference frequency OMEGA to provide for extended regions of unambiguous phase measurements over individual measurements alone. The utility of difference frequency OMEGA is obviously contingent on the accuracy with which this difference frequency phase can be measured and the quality of any skywave corrections if these are required.

In ref. 23 Pierce has found that with $a_0 = a_2 = 0$ and $a_1 = -2.26$ and $a_3 = 3.26^*$ that the composite phase data at Cambridge were essentially constant in time over several days. Using (3-1) the composite phase in cec at 10.2 kHz is

$$\phi_{\text{comp}}(t) = 2.445 \phi_{13.6}(t) - 2.26 \phi_{10.2}(t) = \phi_{\text{comp}} \quad (3-4)$$

where the dependence on time was essentially removed with this particular combination of phase measurements of the 13.6 kHz and 10.2 kHz signal phase. It can be noted from observation that the composite phase of (3-4) is not the phase of the simple difference frequency (3.4 kHz) unless some form of cycle counting is used. The particular values of a_1 will, in general, provide a time independent composite phase measurement only at one location. Variations may be small but will exist since phase velocities do change with position as a result of varying ground conductivity and varying ionospheric height.

3.3 Difference Frequency Diurnal Variation

The diurnal variations of a difference frequency can be analyzed by using (3-1) with appropriately designated constants. Equation (3-2) provides the 3.4 kHz difference phase which may be rewritten as

$$\phi_{3.4} = \phi_{13.6} - \phi_{10.2} \quad (3-5)$$

where the various phases are in cec at the respective frequencies. Using the relationship developed in ref. 1 to determine the daytime and nighttime phase predictions,

*Note $a_1 = -(m - 1)$ and $a_3 = m$ where Pierce gave results in terms of m .

$$\phi_{\text{day}}(13.6) = \left[\frac{c}{v_p(13.6)} \right]_{\text{day}} \phi_o(13.6) \quad (3-6)$$

and

$$\phi_{\text{night}}(13.6) = \left[\frac{c}{v_p(13.6)} \right]_{\text{night}} \phi_o(13.6)$$

where $\phi_o(13.6)$ is the free space phase of the 13.6 kHz signal at a given distance from the transmitter. Thus

$$\phi_o(13.6) = \frac{2\pi d}{\lambda_o(13.6)} = \left(\frac{2\pi f(13.6)}{c} \right) d .$$

Similarly, for the 10.2 kHz signal,

$$\phi_{\text{day}}(10.2) = \left[\frac{c}{v_p(10.2)} \right]_{\text{day}} \phi_o(10.2)$$

and

$$\phi_{\text{night}}(10.2) = \left[\frac{c}{v_p(10.2)} \right]_{\text{night}} \phi_o(10.2) \quad (3-7)$$

where

$$\phi_o(10.2) = \left[\frac{2\pi f(10.2)}{c} \right] d .$$

From (3-6) and (3-7), the diurnal variation in the 3.4 kHz signal can be calculated. Let $\delta\phi(3.4)$ represent the diurnal phase difference $\phi_{\text{night}}(3.4) - \phi_{\text{day}}(3.4)$ so that

$$\begin{aligned} \delta\phi(3.4) = & \left\{ \left[\frac{c}{v_p(13.6)} \right]_{\text{night}} \left(\frac{2\pi f(13.6)}{c} \right) - \left[\frac{c}{v_p(10.2)} \right]_{\text{night}} \left(\frac{2\pi f(10.2)}{c} \right) \right\} d \\ & - \left\{ \left[\frac{c}{v_p(13.6)} \right]_{\text{day}} \left(\frac{2\pi f(13.6)}{c} \right) - \left[\frac{c}{v_p(10.2)} \right]_{\text{day}} \left(\frac{2\pi f(10.2)}{c} \right) \right\} d . \end{aligned} \quad (3-8)$$

Equation (3-8) can be simplified to yield

$$\delta\phi(3.4) = \left[\frac{c}{v_p(13.6)_{\text{night}}} - \frac{c}{v_p(13.6)_{\text{day}}} \right] \frac{2\pi d \times 13.6 \times 10^3}{c} \\ - \left[\frac{c}{v_p(10.2)_{\text{night}}} - \frac{c}{v_p(10.2)_{\text{day}}} \right] \frac{2\pi d \times 10.2 \times 10^3}{c} .$$

The diurnal shift in the 3.4 kHz phase is the difference in diurnal shifts of the 13.6 kHz and 10.2 kHz signal phase at a given distance. Using tabulated values of nighttime and daytime phase velocities for the 10.2 kHz and 13.6 kHz signals from Wait and Spies (ref. 28) for $\sigma_g = 1 \text{ mmho/m}$ and $\beta = 0.5 \text{ km}^{-1}$,

h = 90 km	h = 70 km
$c/v_p(13.6)_{\text{night}} = 1.00291$	$c/v_p(13.6)_{\text{day}} = 1.00075$
$c/v_p(10.2)_{\text{night}} = 1.00130$	$c/v_p(10.2)_{\text{day}} = 0.9980$

where modal interference is neglected, i.e., only mode 1 is considered,

$$\delta\phi(3.4) = \left(\frac{.00216}{c} \right) 2\pi d \times 13.6 \times 10^3 - \left(\frac{.0033}{c} \right) 2\pi d \times 10.2 \times 10^3 \\ = \frac{2\pi d \times 10.2 \times 10^3}{c} \left[\frac{4}{3} (.00216) - .0033 \right] \\ = \frac{2\pi d \times 10.2 \times 10^3}{c} [-.00042] . \quad (3-9)$$

Comparing the diurnal shift of the 3.4 kHz phase to that of the 10.2 kHz phase,

$$\left| \frac{\delta\phi(3.4)}{\delta\phi(10.2)} \right| = \frac{.00042}{.0033} = .127 .$$

Since 1 cec at 3.4 kHz is equal in distance to 3 cec at 10.2 kHz, the corresponding distance error in the 3.4 kHz diurnal shift is $3 \times .127 = .381$ of the diurnal distance error of the 10.2 kHz shift. Thus, if the diurnal shift of the 10.2 kHz signal phase is 20 cec of 10.2, then the expected diurnal shift of the 3.4 kHz signal phase is only about 7.6 cec of 10.2. Using the values of phase velocity given, it can also be shown that this 20 cec diurnal shift in the 10.2 kHz corresponds to a 13.4 cec shift in the 13.6 kHz phase in cec of 10.2 (17.5 cec shift in cec of 13.6).

Using Pierce's values for phase velocities, (ref. 23),

$$\left(\frac{c}{v_p(13.6)}\right)_{\text{night}} = 1.00250 \quad \left(\frac{c}{v_p(13.6)}\right)_{\text{day}} = 1.00035$$

$$\left(\frac{c}{v_p(10.2)}\right)_{\text{night}} = 1.00040 \quad \left(\frac{c}{v_p(10.2)}\right)_{\text{day}} = 0.999730$$

the diurnal phase change in the 3.4 kHz signal is

$$\begin{aligned} \delta\phi(3.4) &= \left(\frac{.00215}{c}\right) 2\pi d \times 13.6 \times 10^3 - \left(\frac{.0031}{c}\right) 2\pi d \times 10.2 \times 10^3 \\ &= \frac{2\pi d \times 10.2 \times 10^3}{c} (.00023) \end{aligned}$$

$$\text{and } \left| \frac{\delta\phi(3.4)}{\delta\phi(10.2)} \right| = \frac{.00023}{.0031} = .0742$$

such that a 20 cec diurnal shift of the 10.2 kHz signal phase in cec at 10.2 will yield a $(20)(.0742)(3) = 4.5$ cec shift in the 3.4 kHz signal phase in cec of 10.2. The 20 cec shift in the 10.2 kHz signal corresponds to a 13.8 cec shift in the 13.6 kHz phase in cec of 10.2 (18.5 cec shift in cec of 13.6).

From this analysis several conclusions can be drawn. The diurnal shift of the 3.4 kHz signal phase will be reduced from that of the 10.2 kHz and 13.6 kHz signal phase. Thus, navigation without corrections using the 3.4 kHz signal can be more accurate than with either of the component frequencies alone. Secondly, the diurnal error in the 3.4 kHz signal phase is monotonic with respect to distance from the transmitter, since the phase

velocity differences create essentially linear phase changes as a function of distance between transmitter and receiver. Thirdly, it is reasonable to expect the 13.6 kHz diurnal phase difference measurement in cec at 13.6 to be numerically very nearly the same as the 10.2 kHz diurnal phase difference measurement in cec at 10.2. This is to say that the frequency dependence of the diurnal change in relative phase velocity is such that the change at 13.6 kHz is on the order of 75% (3 to 4) of the change at 10.2 kHz.

3.4 Composite Error Form

Consider the composite phase error. Let the true value of phase at each individual OMEGA frequency be the chart phase which is determined on the basis of a constant phase velocity and the frequency of interest. Then the chart composite phase in units of cec at 10.2 kHz as given by (3-1) becomes

$$\phi_{\text{comp}_c} = a_0 + a_1 \phi_{10.2c} + a_2 \phi_{11.3c} + a_3 \phi_{13.6c} \quad (3-10)$$

where the time variable can be disregarded since the chart value of phase is time invariant by definition. It should be noted here that for any given set of a_i and using LOP phase measurements a new OMEGA chart could be constructed and used as a navigation chart.

Assume some particular set of a_i , say \hat{a}_i . Then, at some particular geographical position (3-10) is used to express the composite LOP chart phase as

$$\phi_{\text{comp}_c} = \hat{a}_0 + \hat{a}_1 \phi_{10.2c} + \hat{a}_2 \phi_{11.3c} + \hat{a}_3 \phi_{13.6c} \quad (3-11)$$

The actual measured $\phi_{\text{comp}}(t)$ will be that given by (3-1) with $a_i = \hat{a}_i$ such that the composite phase error can be expressed using (3-11) and (3-1) as

$$\begin{aligned} \epsilon_c(t) = & \hat{a}_1(\phi_{10.2}(t) - \phi_{10.2c}) + \hat{a}_2(\phi_{11.3}(t) - \phi_{11.3c}) \\ & + \hat{a}_3(\phi_{13.6}(t) - \phi_{13.6c}) \end{aligned} \quad (3-12)$$

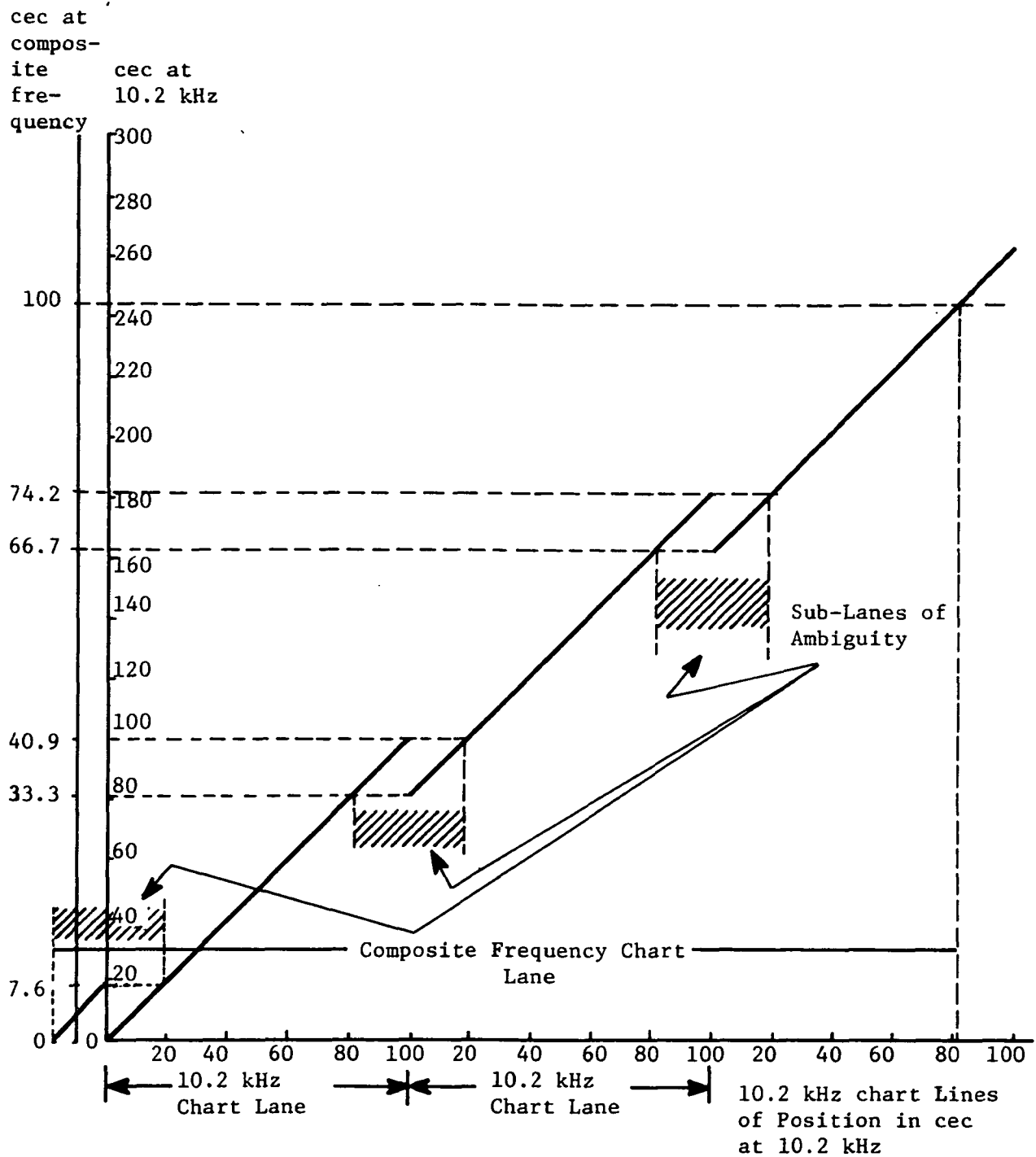


Fig. 3-1. Composite OMEGA lane related to 10.2 kHz chart lanes.

The composite error given in (3-12) is generally time dependent and is related to the errors in the phase measurements at the individual frequencies. Assume that the particular set of \hat{a}_1 used in (3-12) is such that the composite LOP phase does not vary with time over some given period at some particular location such as those found by Pierce for individual phase measurements leading to (3-4). Then the composite error can be expressed using (3-12) as

$$\epsilon_c = K - \phi_{\text{compc}} = K' \quad (3-13)$$

and is not time dependent. Thus a given location would have associated with it a given error, e.g., K' which is constant over a given time, perhaps several days or even weeks. If spatial variation is small, which should be the case considering the source of this variation then a given error would be constant over a region for this period of time. These errors can be thought of as relating to a situation where corrections are required to produce the composite chart values from the measured composite phase. Thus in this sense composite OMEGA might afford good navigational accuracies with a much reduced set of skywave type corrections over those required for ordinary OMEGA.

Consider a composite OMEGA LOP chart using the relationship in (3-4) to define the composite phase. This chart could basically be superimposed on the existing OMEGA LOP charts for 10.2 kHz. Ground position of each phase line at 10.2 kHz can then be compared to that phase line of the "composite frequency." Figure 3-1 illustrates this mapping, showing that the total lane of the composite frequency phase corresponds to three of the 10.2 kHz lanes. The composite phase varies from 0 to 244.5 cec of 10.2 kHz as the three 10.2 kHz lanes are traversed.

Normally an OMEGA lane is defined as a region of unambiguous phase difference variation such that a given phase measurement is unique within the lane. In composite OMEGA where the composite frequency is not an OMEGA frequency or a simple difference frequency the composite lane, as illustrated in Figure 3-1, is not a region of unambiguous phase points. In fact for the case illustrated here there are three sub-lanes of phase ambiguity within the total composite lane. These are regions where two positions correspond to the same phase reading. Note that the composite lane can be defined in composite frequency cec which are 2.445 cec at

10.2 kHz so that sub-lanes of ambiguity are from 0-7.6 cec, 33.3-40.9 cec and 66.7-74.2 cec at the composite frequency. Thus a composite phase reading of 35 cec of the composite frequency can correspond to two distinct points within the composite lane. They are in fact separated by 18.5 cec of 10.2 kHz which corresponds to approximately 1.5 n.mi. (2.78 km) along the baseline.

Based on this analysis the utility of navigation using the composite concept (other than difference frequency) depends on the ability to map a given composite phase to its proper point on the chart within a composite lane. The sub-lanes of ambiguity can present a problem depending on actual variation of the composite phase in time and space. If the composite phase is constant in time and spatial variations are small when compared to a phase error corresponding to 1.5 n.mi. (2.78 km), then in a mode of continuous tracking it should present no problem to maintain accurate navigation through a sub-lane of ambiguous phase measurement using the constant correction of the type in (3-13). Even if composite phase measurement has this requisite precision one can visualize problems within a sub-lane of ambiguity when a high speed vehicle is maneuvering in this region.

If, however, a means of lane counting is provided for in measuring the 10.2 and 13.6 kHz LOP phases then the composite LOP phase difference of (3-4) is unambiguous throughout the 3.4 kHz lane. In fact, this representation of the composite phase is just another way of combining the 10.2 and 13.6 kHz LOP phase measurements to obtain the 3.4 kHz difference frequency phase.

The concept for actual implementation of a composite system is, of course, contingent on the ability to define a composite phase which is stable and verifying this through experiment. This is a primary interest of this study.

3.5 Experimental Data for Composite OMEGA

The experimental data gathering plan outlined in Chapter 2 is designed primarily from the standpoint of learning more about differential OMEGA. These data however will provide for extensive evaluation of composite OMEGA as well. Navigational accuracy using the uncorrected 3.4 kHz difference frequency can be evaluated over an extensive time period and over the entire

differential region defined in this experiment. Evaluation of accuracies using the 1.1 1/3 kHz frequency will be of interest also, particularly since this has not been extensively documented in the literature. These analyses can provide a better understanding of the capabilities of OMEGA in a lane identification mode.

Furthermore, these experimental data can provide for a better understanding of navigational accuracies using composite OMEGA forms without skywave corrections or with a greatly reduced set of skywave corrections and perhaps a composite OMEGA chart to replace the charts currently used with ordinary OMEGA.

CHAPTER 4

OMEGA EXPERIMENT RECEIVER EQUIPMENT

4.1 General

Two identical OMEGA phase receiver complexes have been assembled and are being deployed and operated by NASA personnel. One of these has been located permanently in a NASA laboratory at the Langley Research Center in Hampton, Virginia. The second complex is installed in a small travel trailer and serves as the mobile receiver. A third complex is presently being constructed and will be used during the final phases of the current data gathering plan.

Each receiver station is equipped with a TRACOR Model 599R receiver used with an external 100 kHz source. Also, a digital phase-locked loop receiver designed and built by NASA personnel is included in each receiver station. The two receiver outputs are commutated and recorded in a fixed data format at 10 second intervals on magnetic tape using a Kennedy Model 1600R incremental digital recorder. At each receiver a single 8.5 ft (2.59 m) vertical whip antenna, TRACOR Model 599-818, and a TRACOR Model 607 active multicoupler are used to provide input signals with separation greater than 50 dB to the two individual receivers. At the base receiver the antenna is roof mounted with approximately 150 ft (45.72 m) of coaxial lead-in. The mobile receiver has an antenna mount affixed to the trailer cabin but the antenna is generally mounted on a building roof or a fire tower. A portable mast tower is also available. The same length of coaxial lead-in is used with the mobile receiver as for the base receiver regardless of how the antenna is placed.

Each receiver station uses a General Radio GR1115 oscillator which provides the 100 kHz external source for the TRACOR 599R and serves as the clock reference source for the digital receiver. These reference oscillators are checked periodically for drift and recalibrated. Over a 12-18 month period they have experienced an average drift of about 1.5 parts in 10^{10} per month. The mobile receiver is powered from available 60 Hz power and is provided with a battery pack reserve power supply for use during power outages. A heater and an air conditioner in the mobile trailer provide for temperature and humidity stability of the equipment environment.

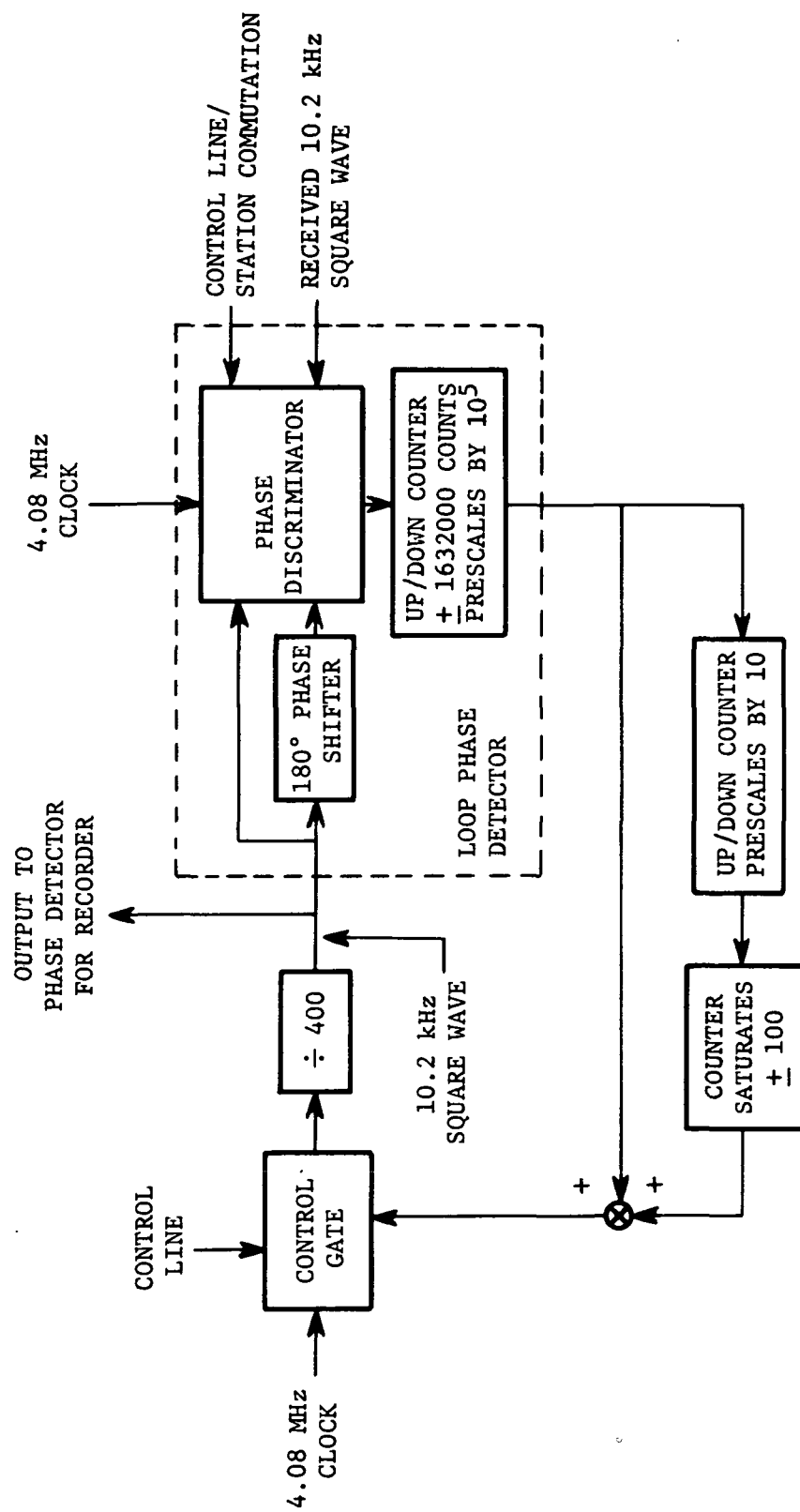


Fig. 4-1. NASA Langley digital phase-locked loop (second order) for OMEGA receiver.

4.2 TRACOR 599R OMEGA Receiver

The square-wave output of the standard TRACOR 599R receiver is changed to digital form and recorded on magnetic tape. Provision is made to record the channel signal strength with one channel recorded during each sample period, each channel sequentially. Receiver RF bandwidth is 3.5 kHz and IF bandwidth is 50 Hz nominal with narrow band IF bandwidth of 0.03 Hz. The sensitivity is 0.01 μ volt with a 50 dB AGC range. The receiver time constant is approximately 10 seconds.

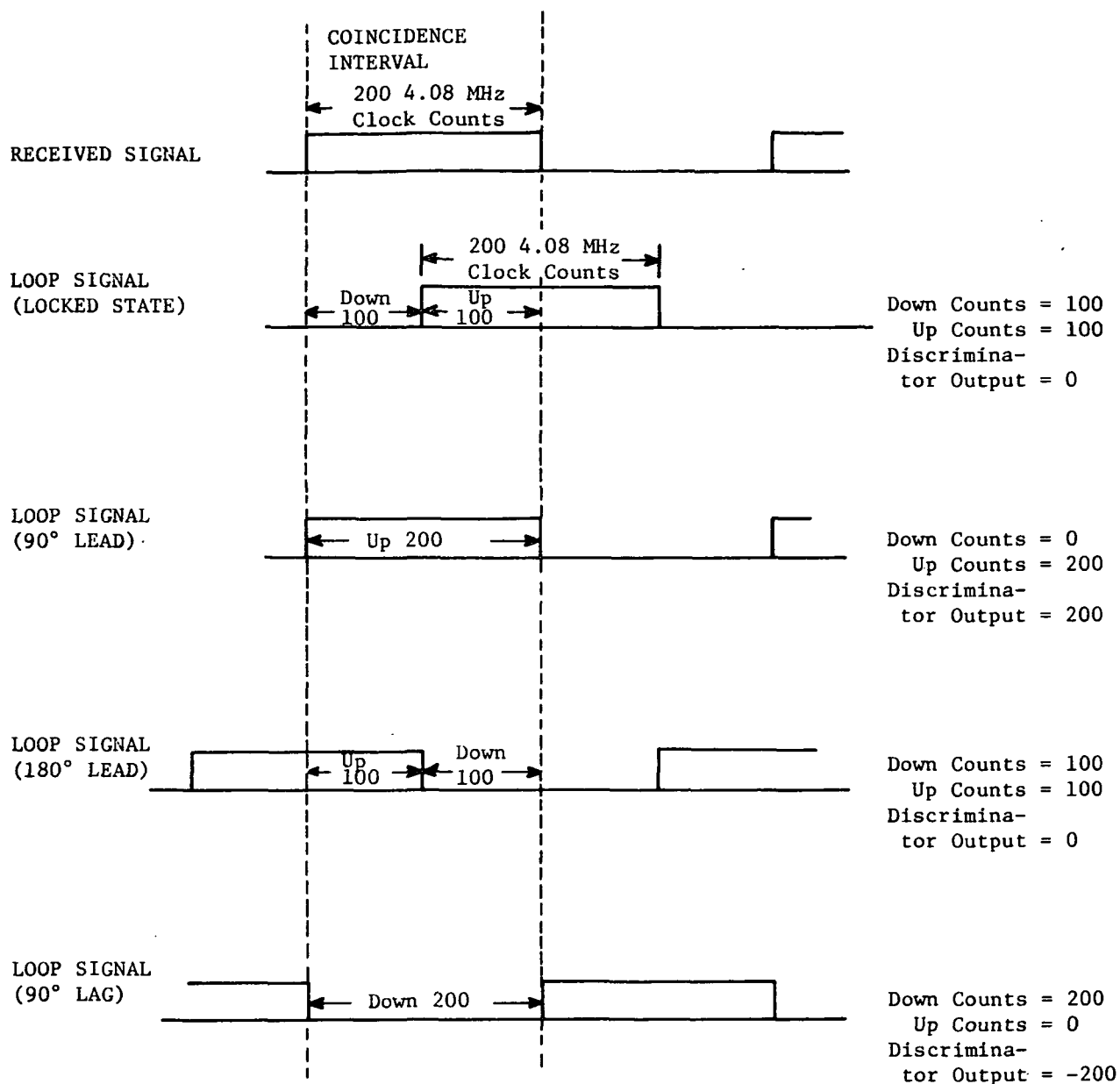
Laboratory tests were run to measure any "S" curve error which might occur in the TRACOR receiver. A signal of known phase was input at the antenna input connector and the output phase was recorded over a period of several minutes. As input phase was varied, no observable variation from the linear curve was experienced. Based on these tests, it was concluded that the receiver measures the actual phase within the 0.25 cec required. Other tests indicated that the receiver phase measurement does not appear to vary with signal strength. These results are not presented here.

4.3 NASA Digital Phase-Locked Loop Receiver

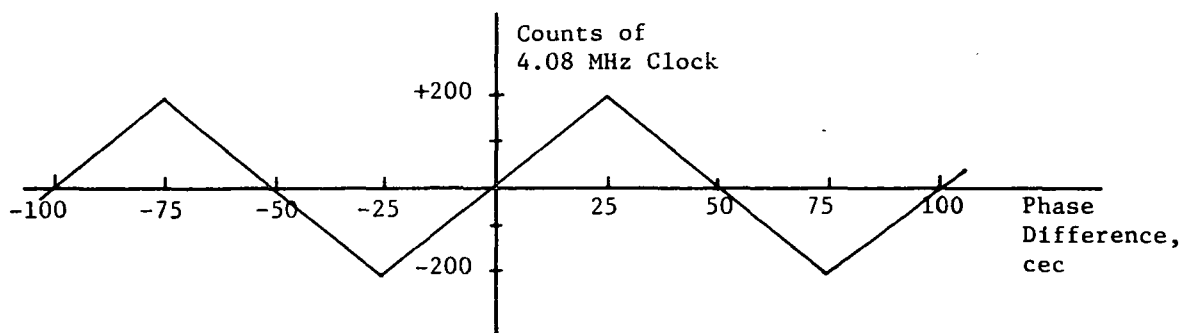
The digital PLL receiver used in the OMEGA experiment was originally designed to represent a second order analog PLL receiver. Several months of data were recorded in this mode. After analyzing receiver performance and some of the errors that were appearing, the loops were changed to first order loops in December 1973. Although there is inherently some phase ramp tracking lag, receiver performance has been considerably more predictable. Performance analysis using a simulation on a PDP-8/e digital computer is presented in Appendix D.

A digitally implemented 10.2 kHz second order phase-locked loop is diagrammed in Figure 4-1. This is representative of all twelve loops within the receiver, with variation in design according to the specific frequency involved.

The control gate/divider chain with the 4.08 MHz clock input is functionally similar to a voltage controlled oscillator. This 10.2 kHz square wave output is the loop signal which has a phase constituting the loop phase. In the phase detector this loop signal phase is compared to the received signal phase to which the loop is assigned. A 180° phase



(a) One Cycle Examples of Relative Loop Phase



(b) Discriminator Characteristic

Fig. 4-2. Characteristics of loop phase discriminator.

shifter provides in-phase and out-of-phase signals to the discriminator. The discriminator operates for 0.8 sec during each 10 second period synchronized with respect to the time of transmission of the OMEGA signal which the loop is tracking. During the 0.8 sec measurement interval an average relative phase measurement is made using an up/down counter which will accumulate counts at the 4.08 MHz rate within a ± 1632000 count range ($1/2 \text{ cycle} \times .8 \text{ sec} \times 4.08 \times 10^6 \text{ counts/sec}$ each cycle up and $1/2 \times .8 \times 4.08 \times 10^6 \text{ counts/sec}$ each cycle down). During each cycle, up counts are accumulated for one-half cycle and down counts are accumulated for one-half cycle. Each cec of phase difference allows four counts to be input to the counter. The up/down counter, which is driven up by the loop signal and the received signal coincidence pulses and down by the out-of-phase loop signal and the received signal coincidence pulses, counts 100 counts per cycle. The resultant output, which is prescaled by 10^5 , is the input to the feedback loop. Figure 4-2 illustrates the discriminator characteristic of this detector.

The input to the up/down counter varies from -200 to +200 counts each cycle as the relative phase varies from -25 cec to +25 cec from lock. The counter output by action of the prescaler provides output counts on the range ± 16.32 during a single measurement interval. Actually only whole counts are output.

The feedback channel consists of a direct feedback and integrated feedback, the sum of which is input to the control gate. The integrated feedback consists of an up/down counter which prescales by 10 and a serial saturating counter which is the integrator. The total number of counts then is fed to the control gate/divider chain which causes loop phase change as a function of the amount of feedback. The control gate/divider chain has an input of pulses and a square wave output at 10.2 kHz. With a divide by 400 in the divider chain the phase position of this square wave is marked by every four hundredth clock pulse. If the loop phase lags, the feedback channel output causes the clock pulse rate to be doubled for a corresponding number of pulse durations to advance the phase position of the loop signal. Alternately, if the loop phase leads, the feedback channel causes the clock pulse rate to stop for a corresponding number of pulse durations, thus retarding the 10.2 kHz loop phase.

Appendix D provides a detailed analysis of this second-order phase-

TABLE 4-1. Summary of Phase Locked Loop Characteristics

LOOP TYPE	a. Noiseless Input			Noise Equivalent Bandwidth B_L	Steady State Ramp Tracking Area
	Gain $(K_o K_d)$	δ	ω_n		
FIRST ORDER	$\frac{K_o K_d}{St K_o K_d}$	—	$\frac{.01632 \text{ rad/sec}}{.0026 \text{ Hz}}$	$\frac{.00408 \text{ Hz}}{.01632 \text{ cec}}$	
SECOND ORDER	$\frac{K_o K_d (s + 1/\tau_1)}{s^2 + K_o K_d s + \frac{K_o K_d}{\tau_1}}$	0.639	$\frac{.0128 \text{ rad/sec}}{.00203 \text{ Hz}}$	$\frac{.00658 \text{ Hz}}{.00203 \text{ Hz}}$	0
b. Noisy Input with Limiter					
(SNR) _i = 10.34dB input to limiter (phase jitter $\sigma = 2.5 \text{ cec}$)					
(SNR) _o = 13.067dB output from limiter					
$\alpha = 0.89467$ limiter suppression factor					
LOOP TYPE	Gain $(\alpha K_o K_d)$	$\delta' = \delta \sqrt{\alpha}$	$\omega'_n = \omega_n \sqrt{\alpha}$	Noise Equivalent Bandwidth B_L	
FIRST ORDER	0.01460	—	.00233Hz	.00365 Hz	
SECOND ORDER	0.01460	0.6044	.00192Hz	.00615 Hz	

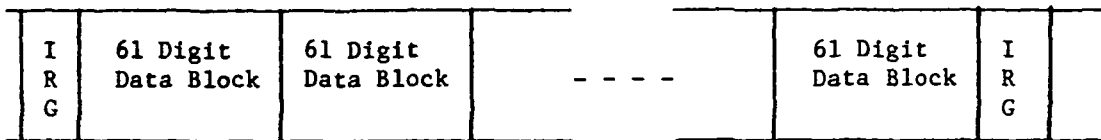
locked loop receiver including performance results using a computer simulation model. These analysis results show that this implementation has a response to a phase ramp input which is slightly underdamped. This can lead to low frequency distortion in tracking a received phase with the oscillatory period of the response dependent on the slope of the ramp, and this oscillation would be very difficult to remove from the data. Primarily for this reason, the digital receiver was changed to a first-order loop, accomplished by simply disconnecting the integrated feedback channel of Figure 4.1. This leaves only the direct feedback channel. This receiver is also analyzed in Appendix D. As expected, the first-order loop receiver will not track a phase ramp input perfectly. The loop ramp does have the same slope as the input ramp (steady state) but there is a constant offset or lag in the phase response. This time lag was calculated and measured to be 61.27 sec of loop operation, which is slightly more than six 10-sec measurement intervals. The corresponding phase lag is

$$\Delta\epsilon_{ss} = 61.27 \Delta\omega$$

where $\Delta\omega$ is the phase ramp input in cec/sec and $\Delta\epsilon_{ss}$ is in cec. Table 4-1 presents a summary of receiver characteristics as determined in Appendix D.

4.4 Recorded Phase Data

Phase data output from the two receiver equipments are recorded on digital tape at 10-sec intervals in an even parity BCD format at 556 ips (14.12 m/sec). Sixteen relative phase readings are recorded, including phase from transmitter stations A, B, C, and D at 10.2, 11 1/3, and 13.6 kHz from the digital phase-locked loop and phase from these four transmitters at a selected frequency from the TRACOR 599R receiver. To complete a logical record of 61 digits of recorded data, a receiver unit code and a time code with day, hour, minute and second are recorded along with a received signal strength measure in accordance with the format of Figure 4-3. Eight blocks including eight sample points (80 sec) compose one physical record of 488 digits. Each physical record is automatically separated by an interrecord gap.



8-Data Blocks of 61 Digits Each
Comprise One Logical Record (488 Digits)

Data Block

Word #	No. of Digits	Content (Note: Sign is in last digit.)
1	3	Norway 10.2 kHz
2	3	Norway 13.6
3	3	Norway 11.3
4	3	Tracor Chan 1 (Norway)
5	3	Trinidad 10.2
6	3	Trinidad 13.6
7	3	Trinidad 11.3
8	3	Tracor Chan 2 (Trinidad)
9	3	Hawaii 10.2
10	3	Hawaii 13.6
11	3	Hawaii 11.3
12	3	Tracor Chan 3 (Hawaii)
13	3	North Dakota 10.2
14	3	North Dakota 13.6
15	3	North Dakota 11.3
16	3	Tracor Chan 4 (North Dakota)
17	3	Signal Strength (Variable Stas.)
18	10	Receiver I. D. Digit Minute - 2 Digits Day - 3 Digits Second - 2 Digits Hour - 2 Digits

Figure 4-3. Digital raw data tape format (7-track tape).

Phase data from the digital phase-locked loop receiver are recorded as a number of 4.08 MHz clock counts so that at 10.2 kHz the recorded phase is in the range ± 200 for a 0-100 cec relative phase measure. The 11 1/3 kHz measure is in the range ± 180 counts and the 13.6 kHz measure is in the range ± 150 counts. Phase data are relative to the internal oscillator phase and are measured within one full cycle to the nearest approximately 0.25 cec of 10.2 kHz. In Appendix E there is a more detailed discussion of how phase measurement data are obtained from the recorded clock counts.

4.5 Clock Time

Within each receiver complex is a special digital clock which provides time in day-hour-minute-second as output to the digital tape. This clock is synchronized at each station using VHF receiver tuned to WWV. The clocks are set at the beginning of each data recording period by the respective operator so that synchronous phase measurement and recording takes place at the remote receiver sites. This provides time labeling of recorded phase which has proven to be within 2-3 seconds apart in all cases. Normally the receivers are set up at the beginning of each recording period and left unattended throughout a 3-5 day period. Clock synchronization is then checked at the end of the data period and any drift is noted. Observed clock drift has been less than one second for even the longest periods.

CHAPTER 5

METHODS FOR STATISTICAL ANALYSIS OF DATA

5.1 General

The raw digital data tapes from each receiver station are reformatted into a packed binary form before any analysis is carried out. (See Appendix E.) Several versions of packed binary tapes are used. Additionally, provision has been made to edit the packed binary tapes. (See Appendix F.) Editing is required to eliminate data which are obviously not valid. Bad data can be caused by a number of events. Transmitter stations which are not on the air or which may be down for short periods create recorded data which should be exempted from analysis. These are usually very easy to recognize as the receivers are not tracking any signal and operate in a searching mode. At times, spurious phase jumps which the receivers are incapable of tracking occur in the data, even when the signal is present. Generally these are attributable to digital noise and are not included in analysis. Since the digital phase-locked loop receivers have been changed to first order loops these occurrences have become very infrequent. There have been some recorder errors which have caused parity errors. The editing software is general and allows for combination computer editing and hand editing.

In the course of creating packed binary tapes for computer analysis, generally a plot of the recorded phase information is obtained. From this point editing of the packed binary tapes is provided and then tapes can be merged with special skywave corrections (see Appendix G) to form skywave corrected data, or used without corrections as input to the various analysis routines.

5.2 Variables for Statistical Analysis

OMEGA phase variables can be calculated as desired once packed binary phase data tapes are created. The analysis software can be used with either unedited or edited data. It should be noted that no provision has been made in the receivers for lane counting. Therefore, all phase values

are scaled on a 0-100 cec range at any given frequency. When a variable for analysis is calculated, i.e., differential error, LOP measurement error, etc., the phase values are scaled on a range $(-50 + \text{True Value}, \text{True Value} + 50)$, where the "True Value" is specified externally. True Value might be a chart value, a data average or some other well-defined value about which a measure of variation is desired.

For differential OMEGA analysis, the differential error variable can be formed with or without skywave corrections. Without skywave corrections, data from two receiver stations are subtracted to form a merged packed binary tape. Sample times may be matched or staggered to form a real-time LOP phase difference or a time-delayed phase difference. When the data are scaled with a true value of the LOP phase difference, the resulting measure is a differential error measure. Data from two receiver stations at the same location provide a measure of inherent receiver bias so that as receiver locations are displaced analysis of the data can show this effect directly. To provide a skywave corrected differential error variable, the single station packed binary tapes are first merged with the special skywave correction data (see Appendix G) and two single station skywave corrected tapes are merged and scaled with the true value.

For ordinary OMEGA error analysis the LOP data from a given single station packed binary tape (words 8-15 of each logical record--see Appendix E) can be analyzed with or without skywave corrections after being scaled with a true value. Analysis of uncorrected ordinary OMEGA data can be complicated in situations where variations from the true value are greater than 50 cec since this results from phase measurement crossing a lane boundary and the receivers have no provision for discriminating between lanes--only between phase values within a lane.

For composite OMEGA analysis the single station data will have to be handled in a special manner. The LOP phase data at one frequency would be combined with the corresponding LOP phase data at the one or two other frequencies according to the composite formula (placed in the first segment of each data word in each logical record--see Appendix E). This could be accomplished using skywave corrected or uncorrected data depending on the type of analysis desired.

When two signal station data tapes are merged, there are also data available which are the differences between relative phase measurement of each transmitted signal at the two receiver locations (words 2-6, word 7 segment 1--see Appendix E). The mean of this difference represents the phase difference between the two receiver station local oscillators. Any relative oscillator drift will show up in the merged data as a linear slope in plots of the data. Uncorrelated variations of a given signal at two receiver stations can be measured directly which can provide a method of delineating contribution to differential and composite OMEGA error. Side-by-side data (two receiver stations at the same location) can provide additional data on receiver repeatability.

In all the variables described, real-time data are accumulated by comparing data recorded at the same time (within 10 sec). For variations with time delay some time shift is made so that data records with different time code identifiers are merged.

5.3 Statistical Calculations

The procedure for direct statistical calculations is basically the same regardless of the variable of interest. A packed binary tape is created with the desired variable for analysis. (See Appendix E.) Certain external information is specified to the analysis software and statistics are provided as output. This section describes the software package available at the current time. Future modifications will be made to provide more extensive capability as data collection and analysis proceed.

For the data variable of interest, Appendix H describes a software package which provides hourly and seasonal mean, standard deviation, and rms output using input in the packed binary format. A season is defined as more than one hour and is only limited by the number of hours of data on a given input tape. Provision is made for sample averaging of the 10 sec sample value of the data variables as specified by the user.

To calculate the statistical mean of the variables of interest, the hourly estimate of the mean for the k th hour is

$$\hat{\mu}_k^* = \frac{1}{N_k} \sum_{i=1}^{N_k} x_{i_j} \quad N_k \leq 360 \quad (5-1)$$

where x_{i_j} are the 10 second samples of data of variable j during hour k which may have up to 360 samples of data. If data editing has exempted some data or if an hour is incomplete for any other reason $N_k < 360$.

The seasonal mean for m hours of data is

$$\hat{\mu} = \left(\frac{1}{\sum_{k=1}^m N_k} \right) \sum_{k=1}^m \left(\sum_{i=1}^{N_k} x_{i_j} \right) \quad (5-2)$$

and can be calculated from the hourly means as

$$\hat{\mu} = \frac{1}{m} \sum_{k=1}^m \hat{\mu}_k$$

To calculate the standard deviation and rms value of the variable of interest on an hourly and seasonal basis it is necessary to accumulate sums of the variable values squared. The unbiased estimate of the hourly variance of variable j is

$$\hat{\sigma}_k^2 = \frac{1}{N_k - 1} \sum_{i=1}^{N_k} (x_{i_j} - \hat{\mu})^2$$

$$\text{or} \quad \hat{\sigma}_k^2 = \frac{1}{N_k - 1} \left[\sum_{i=1}^{N_k} (x_{i_j})^2 - \frac{1}{N_k} \left(\sum_{i=1}^{N_k} x_{i_j} \right)^2 \right] \quad (5-3)$$

The standard deviation is the square root of this variance value for hour k . To obtain a seasonal measure of variance

*The " $\hat{}$ " indicates "estimate".

$$\hat{\sigma}^2 = \frac{1}{\left(\sum_{k=1}^m N_k\right) - 1} \left[\sum_{k=1}^m \sum_{i=1}^{N_k} (x_{i_j})^2 - \left(\frac{1}{\sum_{k=1}^m N_k}\right) \left(\sum_{k=1}^m \sum_{i=1}^{N_k} x_{i_j}\right)^2 \right] \quad (5-4)$$

and the seasonal standard deviation over m hours is the square root of $\hat{\sigma}^2$.

The rms variation for hour k is

$$\hat{rms}_k = \left\{ \frac{1}{N_k} \sum_{i=1}^{N_k} (x_{i_j})^2 \right\}^{1/2} \quad (5-5)$$

and for a season of m hours is

$$rms = \left\{ \left(\frac{1}{\sum_{k=1}^m N_k} \right) \sum_{k=1}^m \sum_{i=1}^{N_k} (x_{i_j})^2 \right\}^{1/2} \quad (5-6)$$

To facilitate the calculations indicated in (5-1) through (5-6) six accumulators and 2 subaccumulators are defined. Three of these accumulators are initialized to zero at the beginning of each hour. Three accumulators are seasonal and are set to zero at the beginning of the total analysis period. In each category there is an accumulator which contains the total number of variable samples, N_k , for the number of samples in an hour and N for the number of seasonal samples, where the seasonal sample number accumulator, N , is $N = \sum_{k=1}^m N_k$; i.e., the hourly accumulator is added to the seasonal accumulator at the end of each hour and then reinitialized. A second accumulator in each category contains a running sum of the variable samples, S_k and S where the hourly accumulator is filled using a subaccumulator which sums up to 90 sample values and is reinitialized to avoid round-off error. At the end of each hour the hourly accumulator is added to the seasonal accumulator and then cleared. The third accumulator in each category operates the same way except that the variable values are squared as they are accumulated in the hourly sum-

square accumulator SS_k and the seasonal sum square accumulator SS . A subaccumulator is also used in conjunction with the hourly sum-square accumulator to avoid round-off error.

In terms of the accumulator just defined the estimates of the statistics given in (5-1) through (5-6) are for the mean

$$\begin{aligned}\hat{\mu}_k &= \frac{1}{N_k} S_k \\ \hat{\mu} &= \frac{1}{N} S ,\end{aligned}\tag{5-7}$$

for the standard deviation

$$\begin{aligned}\hat{\sigma}_k &= \left\{ \frac{1}{N_k - 1} \left[SS_k - \frac{1}{N_k} (S_k)^2 \right] \right\}^{1/2} \\ \hat{\sigma} &= \left\{ \frac{1}{N - 1} \left[SS - \frac{1}{N} (S)^2 \right] \right\}^{1/2} ,\end{aligned}\tag{5-8}$$

and for the rms deviation

$$\begin{aligned}\hat{rms}_k &= \left\{ \frac{1}{N_k} SS_k \right\}^{1/2} \\ \hat{rms} &= \left\{ \frac{1}{N} SS \right\}^{1/2} .\end{aligned}\tag{5-9}$$

It should be noted that the variable of interest is assumed to be scaled by the true value and put in the range $(-50, +50)$ cec prior to input to the accumulators. The resulting statistics are then the mean difference between the variable and the true value, the square root of the squared deviations of the variable about this actual mean, and the square root of the squared deviations of the variable about the true value.

The subaccumulators which were described are to hold the round-off error to a minimum. It is possible that due to the significance of individual samples to large accumulated sums an untenable round-off error might occur, in general. With the CDC-6600 machine this is of no real concern because of the 60 bit word length. With a smaller word size, machine round-off error of several representative hours of data was checked and found to be insignificant. Nevertheless this feature has been retained.

Several computer routines have been developed by NASA Langley personnel to provide data analysis capability. These will be mentioned here but are documented elsewhere (ref. 30).

A routine to provide Varian plots of the 10-second sample values is available. Simultaneous plots of several variables as a function of time can be run. About four variables per plot are all that can be conveniently read and interpreted. The variables are scaled on a range of (0,100) cec and can be plotted for the duration of a data tape using various time scales. These are essential as an analysis tool. Many anomalies are easily recognized visually but would be extremely difficult to detect using the computer because of the difficulty in specifying the criteria in a computerized algorithm.

A general routine to provide probability density functions (pdf), cumulative probability distribution functions (cdf) and modified cumulative probability distribution functions (Mcdf) is also available. These functions can be output for specific daytime periods, e.g., daylight, nighttime, sunrise, sunset, defined in terms of a starting and ending time over the duration of a given data gathering period. Simple statistics are calculated and the data are plotted in histogram form so that quantization of the data is necessary. The pdf routine provides a plot of the relative frequency of occurrence of the variable over the range of the variable in histogram form, thus, it is a discrete pdf. If this function is integrated in steps from the lower limit of the variable range to an upper limit which is changed and varied over the entire range then the result is the cumulative distribution function. The cdf routine

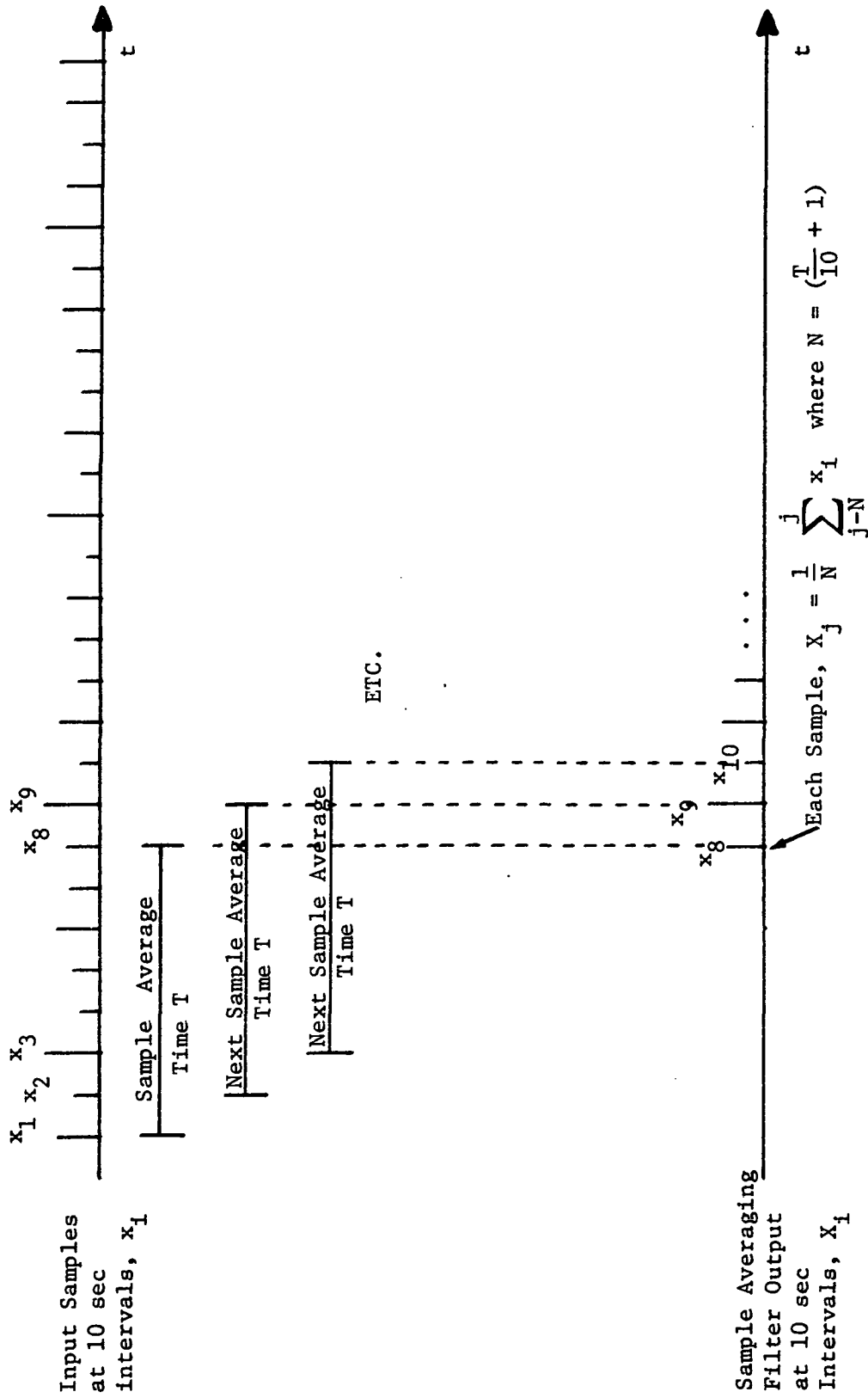


Fig. 5-1. The sample averaging digital filter.

provides this function in histogram form which indicates the probability that the variable will assume a phase equal to or less than a given value for each value in its range. Along with this a modified cdf routine provides a histogram plot of the probability that the phase will be no greater than a specific deviation from the mean value or a specified true value where the deviation is varied in discrete steps from zero to the maximum for the specific variable of interest.

The programs to convert the raw data tapes to packed binary format and to merge pairs of packed binary tapes are also available. A separate version of the merge routine is used to merge data in the packed binary format with the associated skywave corrections which are also put in the packed binary format on special tapes (see Appendix G).

Other software has been developed to generate difference frequency data and composite data other than difference frequency in a format compatible with the packed binary format so that the analysis software is applicable.

5.3.1 Sample averaging.— The data analysis program provides for sample averaging. Since the phase data measurements are made at 10 second intervals, sample averaging permits maximum flexibility in changing the effective time constant of the receivers. This enables digital low pass filtering with the passband defined in terms of the period over which samples are averaged. Removal of high frequency variations of phase data can affect the error variance of phase measurement and is a result of interest with all of the OMEGA variables previously described.

The sample averaging is accomplished by averaging the 10 second samples over N sample values to create a digital filter with a 3 dB passband defined by a cutoff frequency of $\frac{2.78}{10N}$ Hz. The effect of this filter compared to an RC filter used in conventional OMEGA receivers to determine the receiver time constant is discussed in Appendix I. In implementing the averaging at the beginning of a new period of data, N of the 10 second sample values are averaged to generate a new 10 second value. The time associated with the new averaged sample is that originally associated with the Nth sample. Adjusting this time association only

alters the phase response of the digital filter and not the amplitude. As each new 10 second sample is processed a new N sample average is generated, always using the last N sample values to form an average sample. This is illustrated in Figure 5-1.

5.4 Regression Analysis Procedure

One of the primary tasks in the analysis of data is to delineate the parameters which affect differential OMEGA error. In performing these parameter sensitivity tests it is desired to determine functional relationships which will in turn enable prediction of differential error. The intent is to generalize these results.

In performing these parameter sensitivity studies the techniques of regression analysis are being employed. Regression analysis simply means functional analysis and the technique is to evaluate, statistically, functional forms which relate a dependent variable to one or more independent variables. Various statistical measures can then be used to determine which functional form is "best" according to some set of criteria. Actual data which include knowledge of the independent variables and the measured dependent variable values are used to define the best analytical relationship.

This section describes the use of regression analysis to evaluate the differential OMEGA error variable. The same techniques do apply for other dependent variables of interest. In fact similar techniques have been used to assist in improving the accuracy of published skywave correction tables used for ordinary OMEGA navigation.

5.4.1 Using Regression Analysis Techniques.— In applying regression analysis techniques, it is necessary to define a dependent variable and then attempt to form a set of independent variables which are related to this dependent variable. Often it is not possible to simply define independent variables which are truly statistically independent, but the regression procedure can provide for this because variable dependencies can be statistically evaluated. The dependent variable is some measure of interest which in effect is to be parameterized, i.e., the independent variables are essentially parameters, the numerical value of which affect the numerical value of the dependent variable. This mapping of independent variable values to dependent variable values describes the functional relationship between the two.

In the experimental situation some set of measurements of the dependent variables is collected. The conditions under which these measurements are made are described in terms of a set of parameter values or independent variable values. A hypothesis is formulated in terms of a function of these parameters which yields a predicted value of the dependent variable given any particular set of parameter values. For the given conditions of the experimental situation, the observed dependent variable values can then be compared to the predicted values and, using statistical methods, the validity of a given hypothesis can be evaluated. In fact, a number of hypotheses can be compared and a "best" hypothesis arrived at according to some defined criterion.

To select a meaningful hypothesis or set of hypotheses it is necessary to obtain as much a priori information concerning variable relationships as possible. Generally, once a hypothesis is defined it is often possible to converge on a better hypothesis through iteration. The iteration procedure basically involves selecting some functional form, evaluating the hypothesis, and then modifying the hypothesis until it is improved. One example of this can be illustrated by considering a situation where there are several independent variables. Experimental conditions could be organized so that the first set of dependent variable measures results from a condition where all but one of the independent variables is held constant. Once a satisfactory functional form for predicting dependent variable values based on assigned values of the remaining independent variable is found, then a second independent variable can be isolated. This procedure can be repeated until a hypothesis involving all the independent variables is determined valid. Even when using this parameter isolation technique, further iteration may be necessary, particularly if any of the set of independent variables is not statistically independent.

5.4.2 Regression Analysis of Differential Error.— In Chapter 2, a discussion of differential error form was presented which analytically related the dependent variable, error, to several of the independent variables. Additionally, other independent variables (Table 2-1) were delineated based on a priori analysis which are believed to have an effect on differential error. An experimental plan was then formulated which provided for variation of the values of these parameters (independent variables)

over a range which could provide experimental measures of the dependent variable over the usable region of differential OMEGA. The variety of receiver sites provides for variation of spatial parameters, for example, and the duration of data collection and the site visitation schedule provide for variation of temporal parameters. Evaluation of functional forms which relate differential error to these spatial and temporal parameters is achieved by obtaining a set of data measurements for each available set of parameter values. Then the regression analysis procedure can be used to determine functions for predicting what the error will be for any given spatial and temporal conditions. The regression analysis can also provide a measure of the confidence in these predictions so that the user can modify the experimental plan and gather additional data to strive for greater confidence in the results.

The experimental plan is designed to cover a period of 12-18 months, and only about 6-8 months of data are available at present for analysis. Of the available data, much has not been edited. Results obtained thus far are presented in Chapter 6 although these are preliminary. Basically, only full daytime periods have been considered. This in effect holds the time-of-day independent variable constant. Major emphasis has been on using the procedure to determine variations with respect to range and azimuth between receivers employed in a differential mode. To attain additional confidence in these results it will be necessary to process data from more receiver sites, and it may also be necessary to add sites to the ones specified in the original plan presented in Chapter 2.

Consider the use of regression techniques to determine the relationship of differential OMEGA error as defined in Chapter 2 to some vector of independent variables, say $\bar{x} = (x_1, x_2, x_3, \dots, x_n)$. Consider $n = 2$ with x_1 the range and x_2 the azimuth between the base receiver and the remote receiver. Let the dependent variable be differential error ϵ_D where the error may be an instantaneous error or a time averaged error with

$$\epsilon_D = \frac{1}{T} \sum \epsilon_D \quad (\text{instantaneous differential error})$$

where the time average may be taken over any specified period.

Consider some hypothesized model which relates daytime time averaged

differential error to range and azimuth by

$$\epsilon_D = f(x_1, x_2) + e \quad (5-10)$$

where e is a random perturbation about the statistical mean $f(x_1, x_2)$. The model assumes this statistical mean function to be deterministically related to x_1 and x_2 which in linear form could be represented as

$$f(x_1, x_2) = a_0 + a_1 x_1 + a_2 x_2 = (1, x_1, x_2) \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix}$$

yielding for (5-16)

$$\bar{\epsilon}_D = X\bar{A} + \bar{e}$$

where $\bar{\epsilon}_D$ is the vector of experimental measurements including, in general, more than one measurement. Correspondingly \bar{e} represents a vector of random perturbations. X is an augmented matrix of the independent variable values (x_1, x_2) for each measurement of the dependent variables. \bar{A} is the vector of unknown coefficients. The least squares regression analysis procedure then yields a set of coefficients

$$\hat{\bar{A}} = (X^T X)^{-1} X^T \bar{\epsilon}_D$$

where " $\hat{}$ " indicates "estimate" and superscript "T" indicates transpose.

The theory yields that the estimate of the time averaged error for a given independent variable set (x_1, x_2) has a variance given by

$$\text{Var} \{ \epsilon_D(x_1, x_2) \} = \sigma^2 [\bar{x}^T (X^T X)^{-1} \bar{x}] = \sigma^2 R(\bar{x}) \quad (5-11)$$

where $\bar{x}^T = (1, x_1, x_2)$, and σ^2 is the variance of the observations with respect to the true model and is estimated by the observed variance of the measurements about the predicted mean values of the differential error for given values of (x_1, x_2) .

Hence by an appropriate method of analysis the quantity in (5-11) above

can be obtained for various values of (x_1, x_2) throughout the range of (x_1, x_2) and plotted. The resulting contours can be compared for various experimental designs of interest, i.e., with different values of (x_1, x_2) (different remote station locations) and with differing numbers of repeat measurements.

The approach can be extended to other function forms to provide a better fit. For example a non-linear relationship in one or more independent variables might be necessary. One alternative might be to define $x_3 = x_1^2$ and then use this procedure to evaluate

$$f(x_1, x_2, x_3) = a_0 + a_1x_1 + a_2x_2 + a_3x_3$$

as a prediction equation for mean differential error.

The set of independent variables can then be expanded so that a final form of the prediction equation is

$$\hat{\epsilon}_D = f(\bar{x})$$

where \bar{x} is a vector of all the variables in Table 2-1 and $\hat{\epsilon}_D$ is a prediction of differential error.

5.4.3 Regression Analysis Output.— The regression analysis procedure being used with the OMEGA data involves the use of a statistical analysis system computer program package (see ref. 31) available on the IBM 370/165 system at the Triangle Universities Computation Center, Research Triangle Park, North Carolina. The system was developed by individuals in the Department of Statistics at North Carolina State University in Raleigh and at present is only available for IBM 360 and 370 systems with at least 140K of core storage. Selected routines from this system are being used to determine a functional form to predict differential OMEGA error. Output will include that described in the following paragraphs.

The total sum of squares, ss_T , is the sum of squared deviations of the dependent variable measurements about their mean. This is a measure of the spread in the data and is usually termed "corrected total sum of squares." This total sum of squares is the sum of squares due to regression, ss_R , plus the sum of squares due to error, ss_E , where

$$ss_T = ss_R + ss_E .$$

The term ss_R is the deviation of each predicted value of the dependent variable using the results of the least squares fit from the mean of the observed values of the dependent variable squared and summed. The term ss_E is the deviation of each observed value of the dependent variable from the predicted value squared and summed.

The degrees of freedom (DF) for ss_T are always one less than the number of observations; for ss_R are always one less than the number of regression coefficients; and for ss_E are the difference between the first two.

The mean square variation is a variance measure defined as the ratio of the sum of squares to the degrees of freedom. If the independent variables do not influence the dependent variable the regression mean square and error mean square are two different estimates of the same variance. Any difference is due to "chance." If they are distinctly different then the dependent variables do provide some explanation of the variation. A statistical "F" test (see ref. 32) is used to determine the degree to which the regression equation predicts the variation in the data. The F value is the ratio of the regression mean square to the error mean square. The F statistic distribution is then used to measure the probability that the particular calculated value can be exceeded if the regression equation does not, in fact, predict the variations of the dependent variable actually observed. A small probability here indicates that the regression equation is significant.

These quantities also provide an R-square value which is the ratio of ss_R to ss_T , which provides a measure of the percentage of variation explained by the regression model. This multiple correlation coefficient has values close to unity for useful regression models.

The residual standard deviation, which is the prediction error standard deviation, is the square root of the quantity ss_E divided by the degrees of freedom for ss_E . This is used to define a coefficient of variation (C.V.) as a percentage of the mean of the observations of the dependent variable. If this percentage is small then the standard deviation of the prediction errors from the mean observation is small compared to the observation mean and provides additional confidence in the stability of the regression equation in predicting the dependent variable.

ED=ANRANGE=CUS(2TH)

ANALYSIS OF VARIANCE TABLE , REGRESSION COEFFICIENTS , AND STATISTICS OF FIT FOR DEPENDENT VARIABLE ED

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	1	1.09405265	1.09405265	11.49487	0.0147	0.65104232	03.42382 X
ERROR	6	0.57106482	0.09517747				ED MEAN
CORRECTED TOTAL	7	1.66511747				0.50850846	-0.48682

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
RC2TH	1	1.09405265	11.49487	0.0147	1.09405265	11.49487	0.0147

SOURCE	B VALUES	T FOR H0:B=0	PROB > T	STD ERR B	STD B VALUES
INTERCEPT	-0.47763115	-4.37772	0.0047	0.10910504	0.0
RC2TH	-0.00978926	-3.39041	0.0147	0.00288734	-0.81058147

OBS NUMBER	OBSERVED VALUE	PREDICTED VALUE	RESIDUAL
1	-0.88291667	-0.47763115	-0.40528551
2	-0.21652778	-0.42220816	0.20572039
3	0.03625000	-0.08102174	0.51727174
4	-0.91652778	-0.97775596	0.06122819
5	-1.31263889	-1.11233596	-0.20040293
6	-0.33111111	-0.39452520	0.06341409
7	-0.02986111	-0.00817821	-0.02168290
8	-0.23805556	-0.01779250	-0.22026306

SUM OF RESIDUALS	=	-0.00000000
SUM OF SQUARED RESIDUALS	=	0.57106482
SUM OF SQUARED RESIDUALS - ERROR SS	=	0.00000000
FIRST ORDER AUTOCORRELATION OF RESIDUALS	=	0.07185972
DURBIN-WATSON D	=	1.51137663

Fig. 5-2. Sample regression analysis output.

The regression sum of squares is partitioned to show the effect of each independent variable. The marginal effect of introducing each variable in sequence is provided as a sequential sum square. Mean squares are calculated to provide an "F test" measure of the relative sequential significance of each independent variable in explaining the variations of the dependent variable. Additionally, the marginal effect of introducing each dependent variable after all the other dependent variables have been introduced is provided using the F test measure of probability. In each case small probabilities indicate large significance.

The regression coefficient values are given with a measure of their significance by testing their calculated value against the hypothesis that the coefficients are zero using the Student "t" test (see ref. 32). If this probability is small then the coefficients are not likely to be zero and another measure of the significance of the model is stated. The standard deviation of the prediction error of each coefficient is also presented.

A table of predicted values of the dependent variable for each set of independent variable values along with residual error between observed value and predicted value is then given. A predicted value is given for each observed value used in the analysis. The first order autocorrelation of the residuals is also included.

These outputs are included for some of the differential OMEGA error observations along with presentation of results in Chapter 6. An example of analysis output is given in Figure 5-2 to illustrate the format of the output which has been explained in the preceding paragraphs.

CHAPTER 6

SELECTED ANALYSIS RESULTS

6.1 GENERAL

As discussed in previous chapters several OMEGA data analysis computer routines have been developed. These have been used with some of the data taken during approximately the first six months of the data gathering period as a basis for the discussion presented in this chapter.

It should be noted that only a small portion of the data has been edited at this time. This is due in part to the fact that the final criteria for selecting bad data have not been completely described. Furthermore, emphasis has been placed on solving several of the problems which were not anticipated and did not show up until the data gathering phase was underway. For example, the digital phase-locked loop receiver loops were changed after several months of data were taken. Therefore, of the first six months of data, about 3 1/2 months are with second order loops and the remainder is with first order loops. Local effects problems have proven to be more significant than anticipated. In some places the 60 Hz interference has been so severe that data had to be discarded. This has made it necessary to select new sites with some associated delay in carrying out the data gathering phase. Instances of time varying modal interference have been observed, and some time has been spent to ascertain that these were truly observed phenomena and not receiver problems.

The regression analysis presented here has been limited to daytime periods for the data available. The daytime data are comparatively very stable and generally require very little editing. Although the data are not edited, a daytime period of 1500-2100 GMT was selected which provided data from eight of the remote sites and from the side-by-side tests which were virtually free of any "loss of track" situations.

It should also be noted that the Navy's schedule for refitting the OMEGA transmitter stations with the necessary equipment to yield 10 kW transmission power has slipped. The North Dakota station came on the air in

Day 270, Hour 20 - Day 271 Hour 1
 Digital PLL Receiver at 10.2 kHz
 Period Mean = 0.83 sec

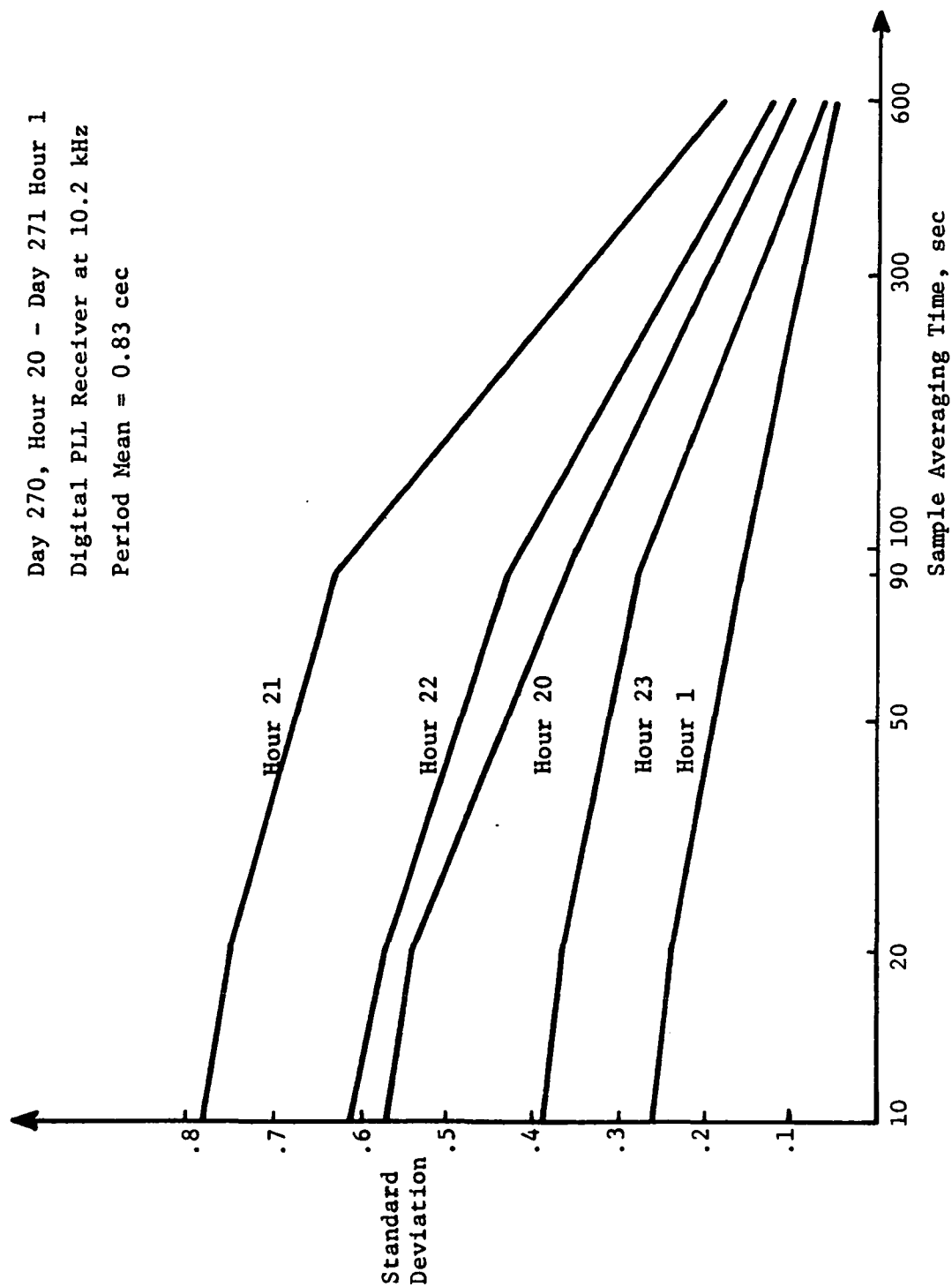


Fig. 6-1. Side-by-side differential error standard deviation vs. sample averaging time, digital PLL receiver at 10.2 kHz, B-D LOP.

mid-1973 at 10 kW. The Norway transmitter did not come on the air until around the first of January, 1974. Trinidad is still at low power (~800 watts) and Hawaii has not been up at all during the data gathering period. During the period September-December 1973 only Trinidad and North Dakota data were recorded. Since January 1974 Norway, Trinidad, and North Dakota data have been obtained. Most of the analysis is therefore confined to the Trinidad-North Dakota (B-D) LOP data.

Additionally, results are necessarily preliminary since the total experimental plan is designed to provide a statistically significant set of data and less than fifty percent of this total has been obtained.

6.2 Receiver Repeatability

Several weeks have been allotted during the course of the experimental plan to gathering data with the receivers at the same location. These periods are interspersed with periods of receivers in remote positions. The side-by-side situations involve placing the mobile receiver complex adjacent to the NASA Langley Research Center laboratory building containing the base receiver and roof-mounting the OMEGA whip antenna near the base receiver antenna. Data taken in this situation permit determination of receiver repeatability. The receivers see the same incident signal from all transmitters and their ability to measure the same phase at the same time, thus determining repeatability, provides an indication of inherent limitations on the achievable differential error, i.e., ability to measure highly correlated signal phase when remote from each other. These side-by-side testing periods are interspersed so that any variations in repeatability with time can be ascertained.

Most of the analysis presented is for data taken during the full daytime period, with both transmitters and receivers in full daylight conditions. This represents the time of most stability in the OMEGA signal and will provide some indication of a lower bound on navigation accuracy, i.e., the best that can be done.

Figures 6-1 through 6-4 provide plots of side-by-side B-D LOP phase measurement error between receivers at all three OMEGA frequencies taken during September 1973. These plots are actually error standard deviation about the observed hourly mean for several hours during the daytime period as a function of the sample averaging time used in analysis. Figure 6-1 is the 10.2 kHz phase error standard deviation with the overall period mean

Day 270 Hour 20 - Day 271 Hour 0
 Digital PLL Receiver at 11 1/3 kHz
 Period Mean = -0.54 cec

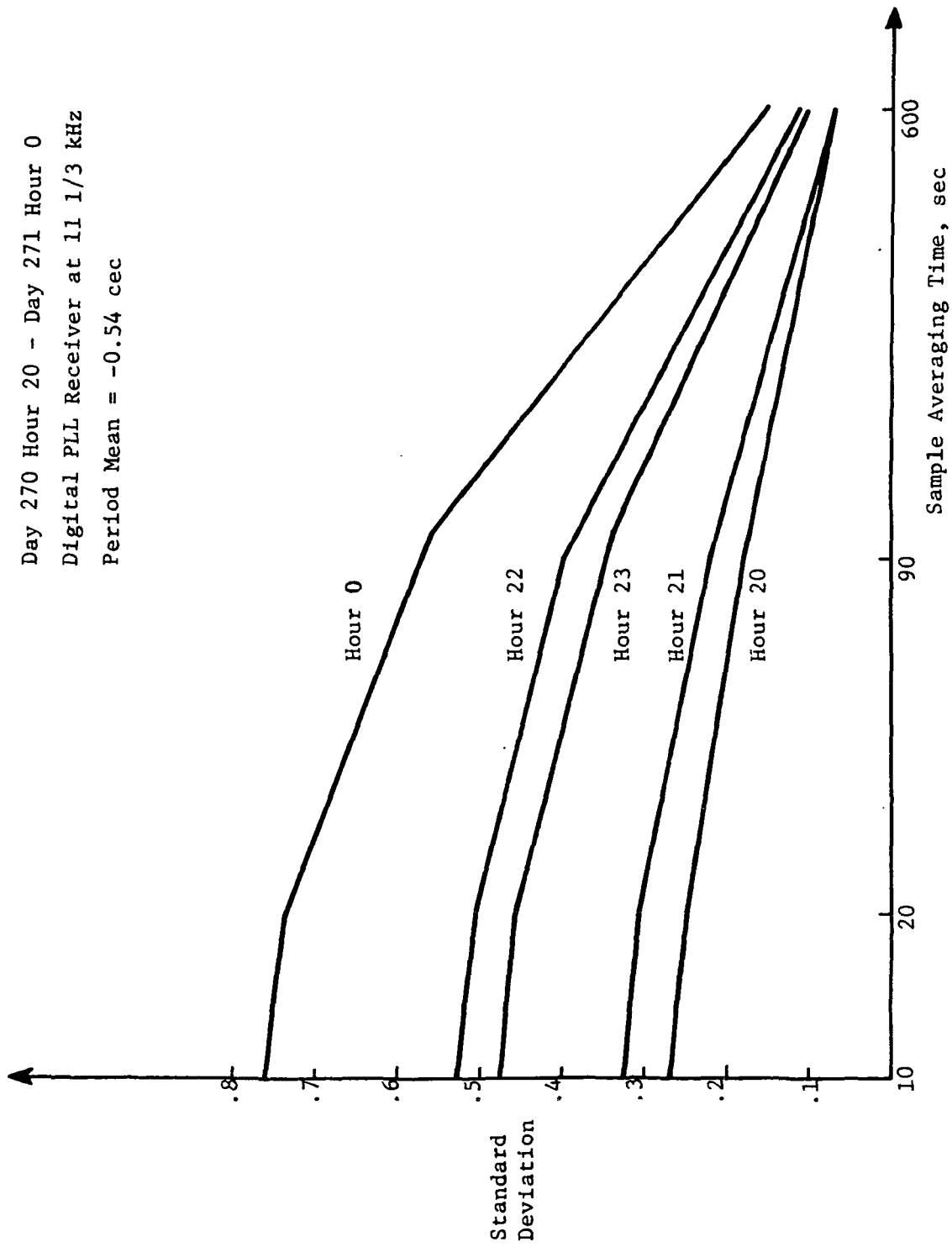


Fig. 6-2. Side-by-side differential error standard deviation vs. sample averaging time, digital PLL receiver at 11 1/3 kHz, B-D LOP.

Day 270 Hour 20 - Day 271 Hour 1
 Digital PLL Receiver at 13.6 kHz
 Period Mean = 1.39 cec

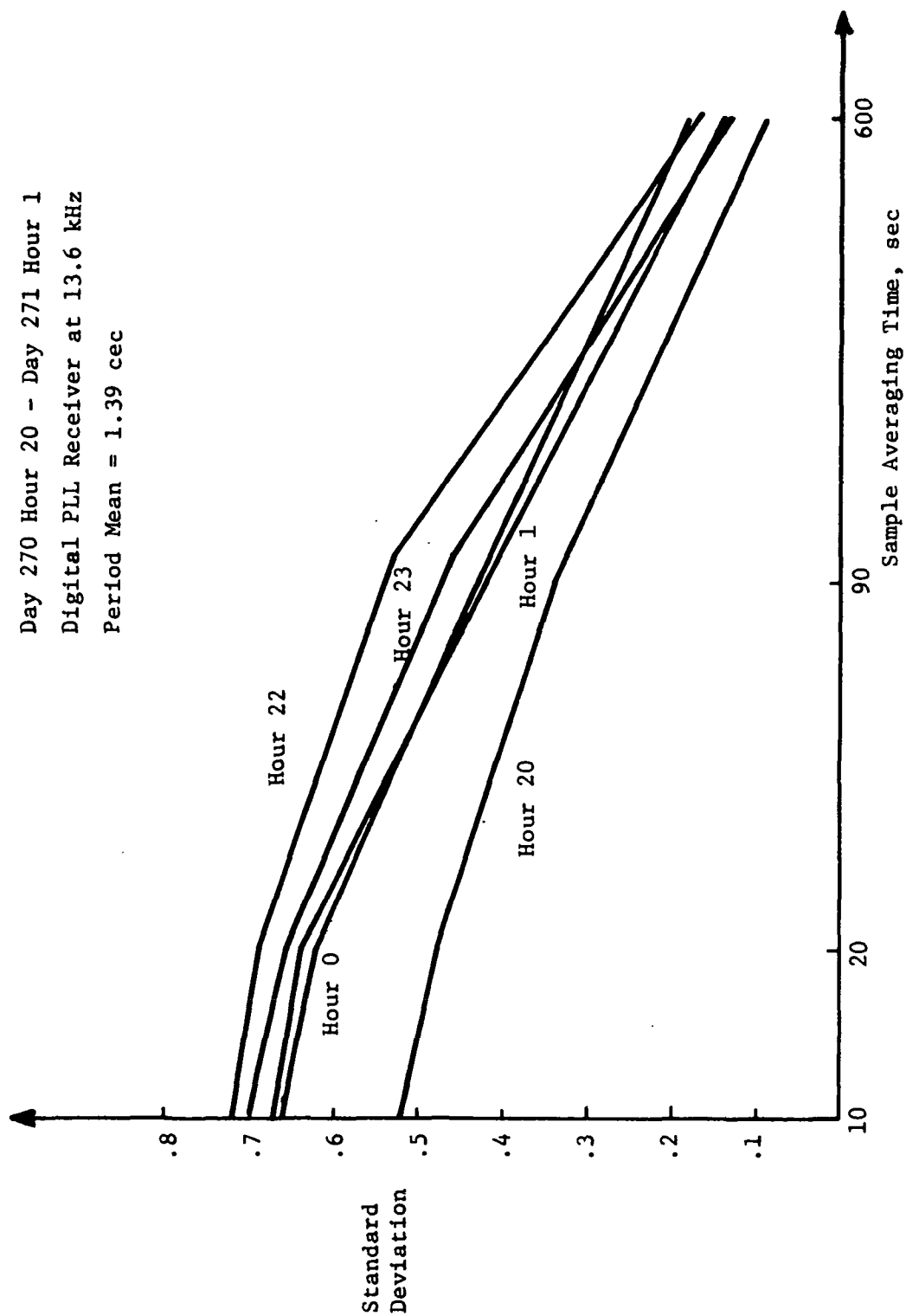


Fig. 6-3. Side-by-side differential error standard deviation vs. sample averaging time, digital PLL receiver at 13.6 kHz, B-D LOP.

Day 270 Hour 20 - Day 271 Hour 1
 TRACOR Receiver at 10.2 kHz
 Period Mean = 0.16 cec

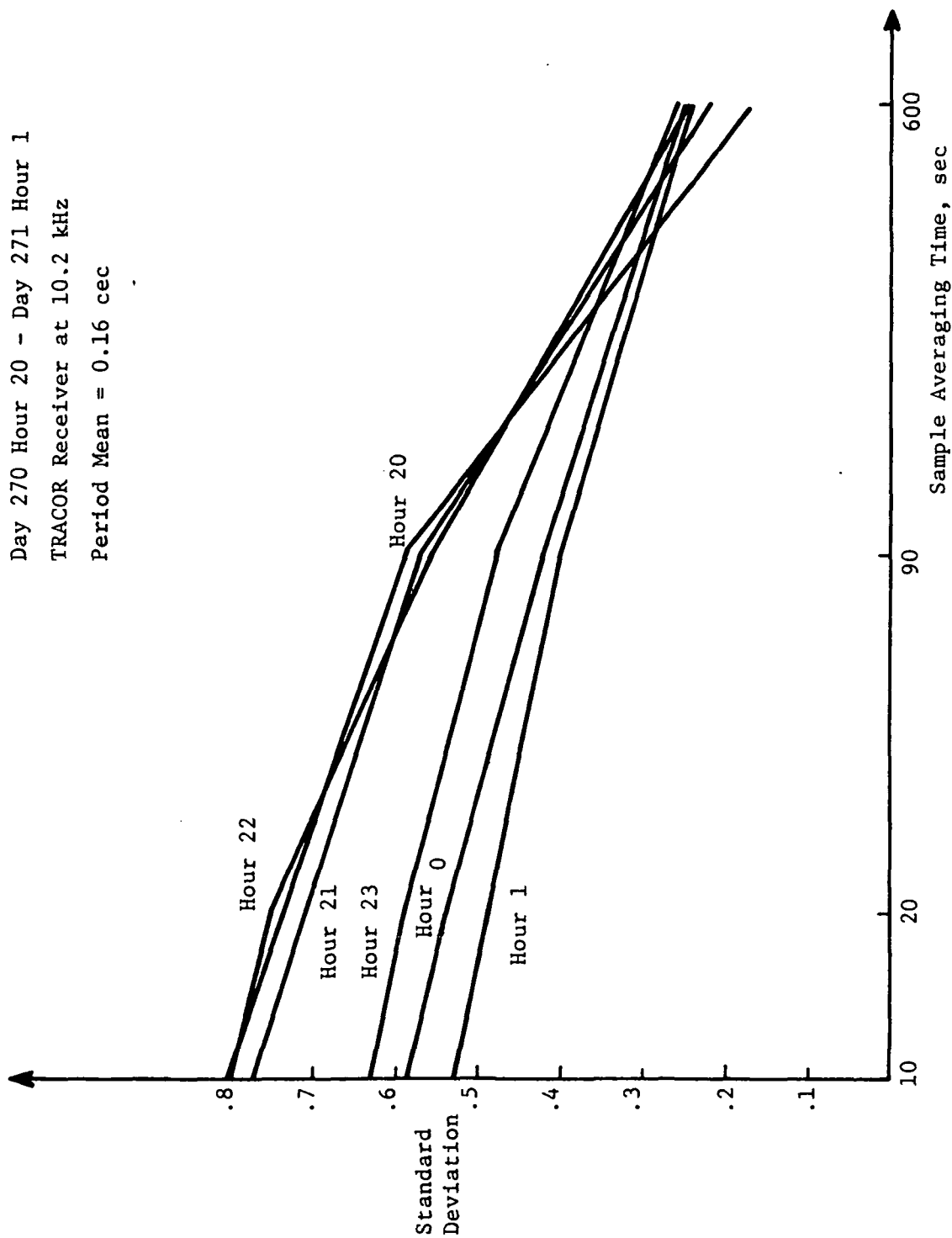


Fig. 6-4. Side-by-side differential error standard deviation vs. sample averaging time, TRACOR 599R receiver at 10.2 kHz, B-D LOP.

of 0.83 cec. Figures 6-2 and 6-3 are for 11 1/3 and 13.6 kHz respectively. Figure 6-4 is for the Tracor receiver at 10.2 kHz. All of these results indicate that the repeatability error standard deviation decreases as the sample averaging time increases. The decrease is close to exponential but the convexity of the curves suggest the decay is perhaps more rapid than simple exponential.

At 10.2 kHz the Tracor receiver error has an average standard deviation just slightly larger than the digital PLL receiver (operated as a second order loop during this period). However the hour to hour variation in the Tracor error appears more predictable. Of all three frequencies the 13.6 kHz shows more hour to hour stability in the digital receiver.

The sample averaging shows that the primary contributions to uncorrelated variations of LOP phase are at the higher frequencies. Since the sample averaging algorithm is really just an implementation of a digital low pass filter (see Appendix I) it can be seen that most of the uncorrelated variations have a period less than 22.8 minutes ($T = \frac{1}{f}$ where $f = \frac{\omega_{3dB}}{2\pi}$ and ω_{3dB} is defined in Appendix I in terms of the averaged time τ). For ten minute sample averaging the standard deviations are generally below 0.20 cec which will map to a maximum standard deviation of approximately 140 feet (42.67 m) of navigation error when using two LOP's with a 90° crossing angle.

Figures 6-5, 6-6, and 6-7 compare hourly standard deviations for several daytime hours for three different side-by-side test periods, one in September 1973, one in early December 1973, and the latter in February 1974. These hourly values represent the data period (2-4 days) standard deviation for that hour using five minute sample averages. The data are unedited and most of these points are all less than .25 cec (navigation error of ~175 feet (53.34 m) with two LOP's). The analysis in Figure 6-7 is with data from the digital receivers with first order loops.

Figure 6-8 provides a comparison of the standard deviation of the hourly side-by-side error of the first order PLL receivers at all three frequencies with the Tracor receiver at 13.6 kHz. With five minute sample averaging reasonably good stability is exhibited with most of the values less than 0.25 cec.

With the receivers separated, the uncorrelated variations increase as in the situation illustrated in Figure 6-9. This shows standard deviation of

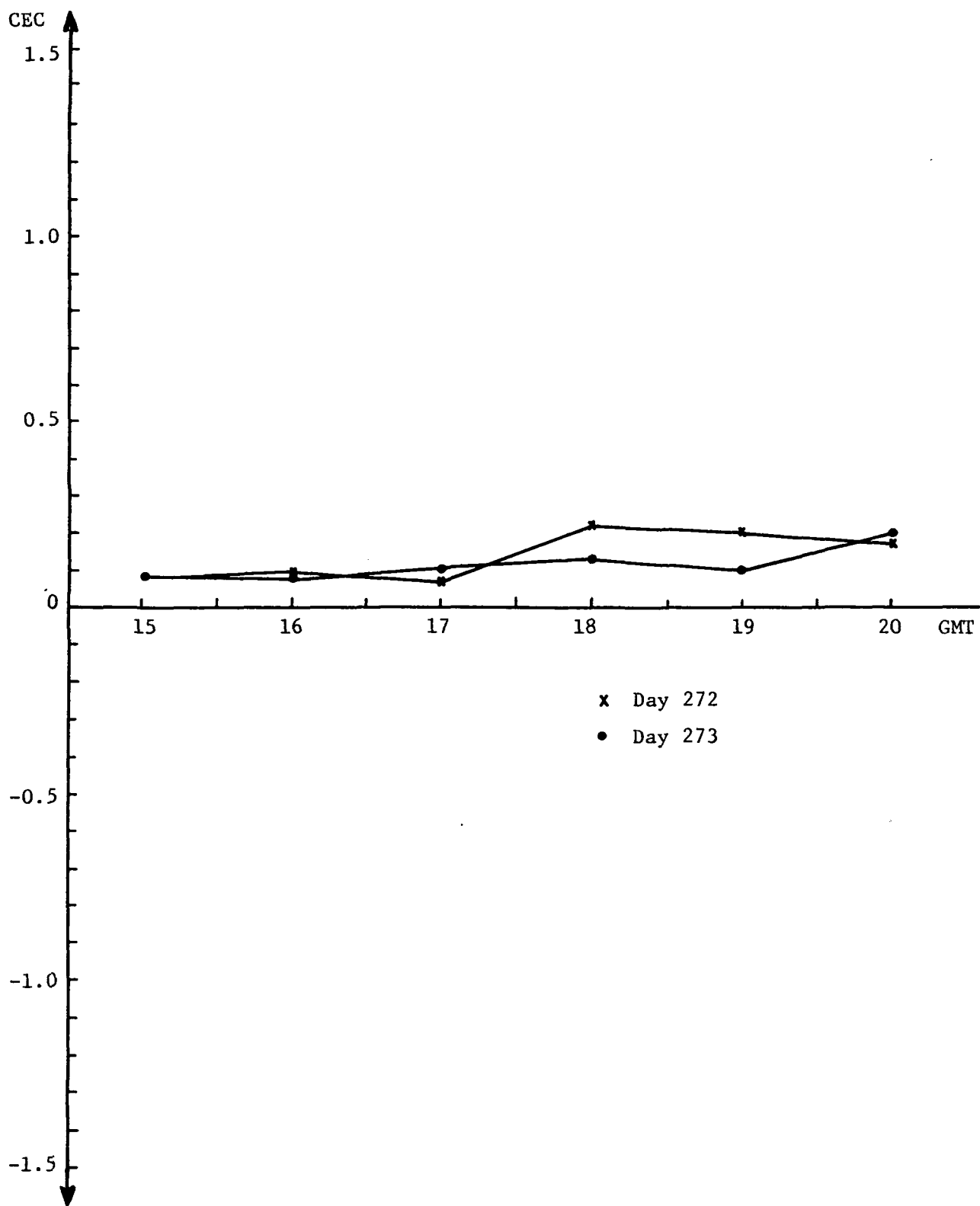


Fig. 6-5. Side-by-side daytime differential error standard deviation vs. Time using 5 min averaged samples, 10.2 kHz, B-D LOP, digital PLL receiver, September 1973.

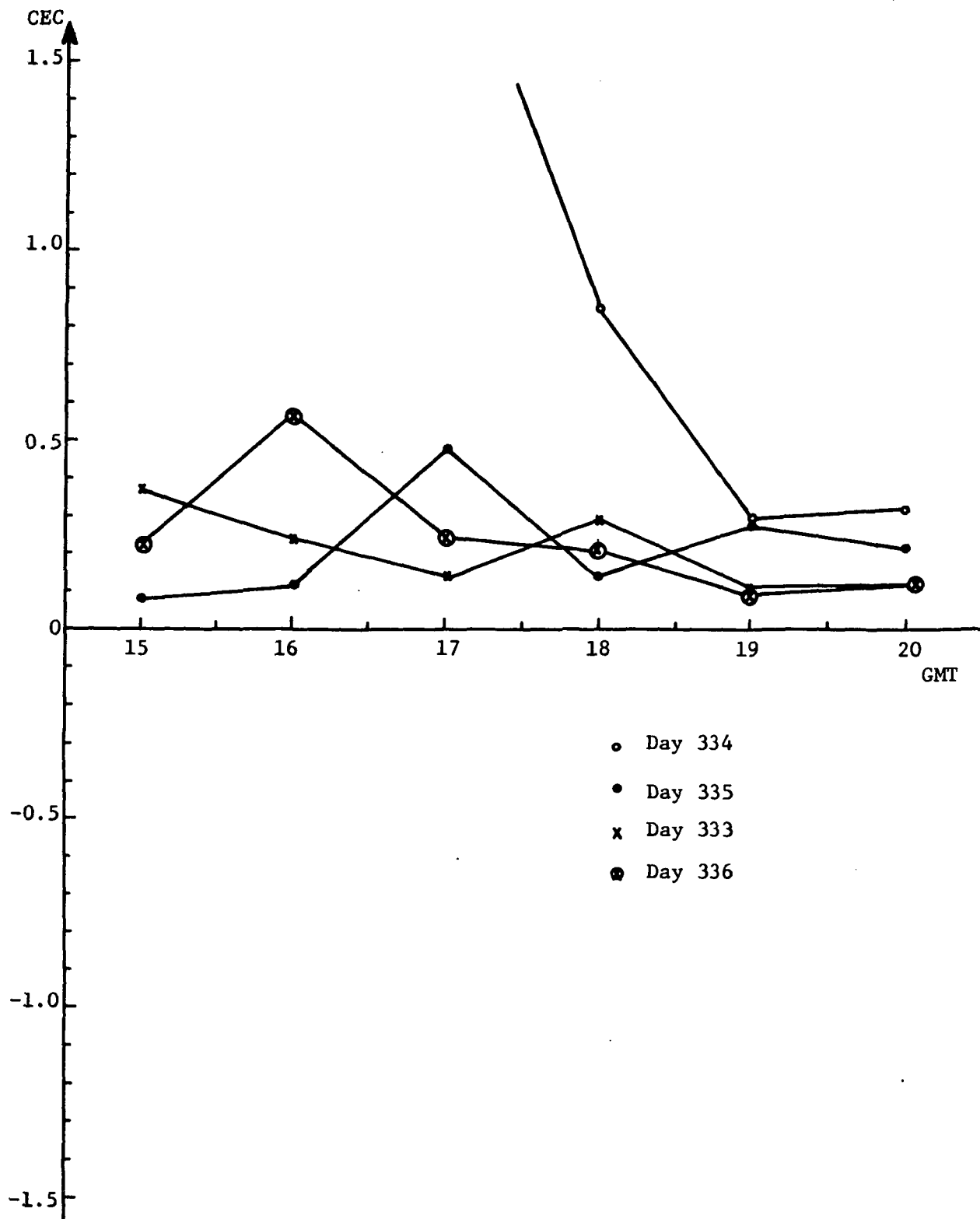


Fig. 6-6. Side-by-side daytime differential error standard deviation vs. time using 5 min averaged samples, 10.2 kHz, B-D LOP, digital PLL receiver, December 1973.

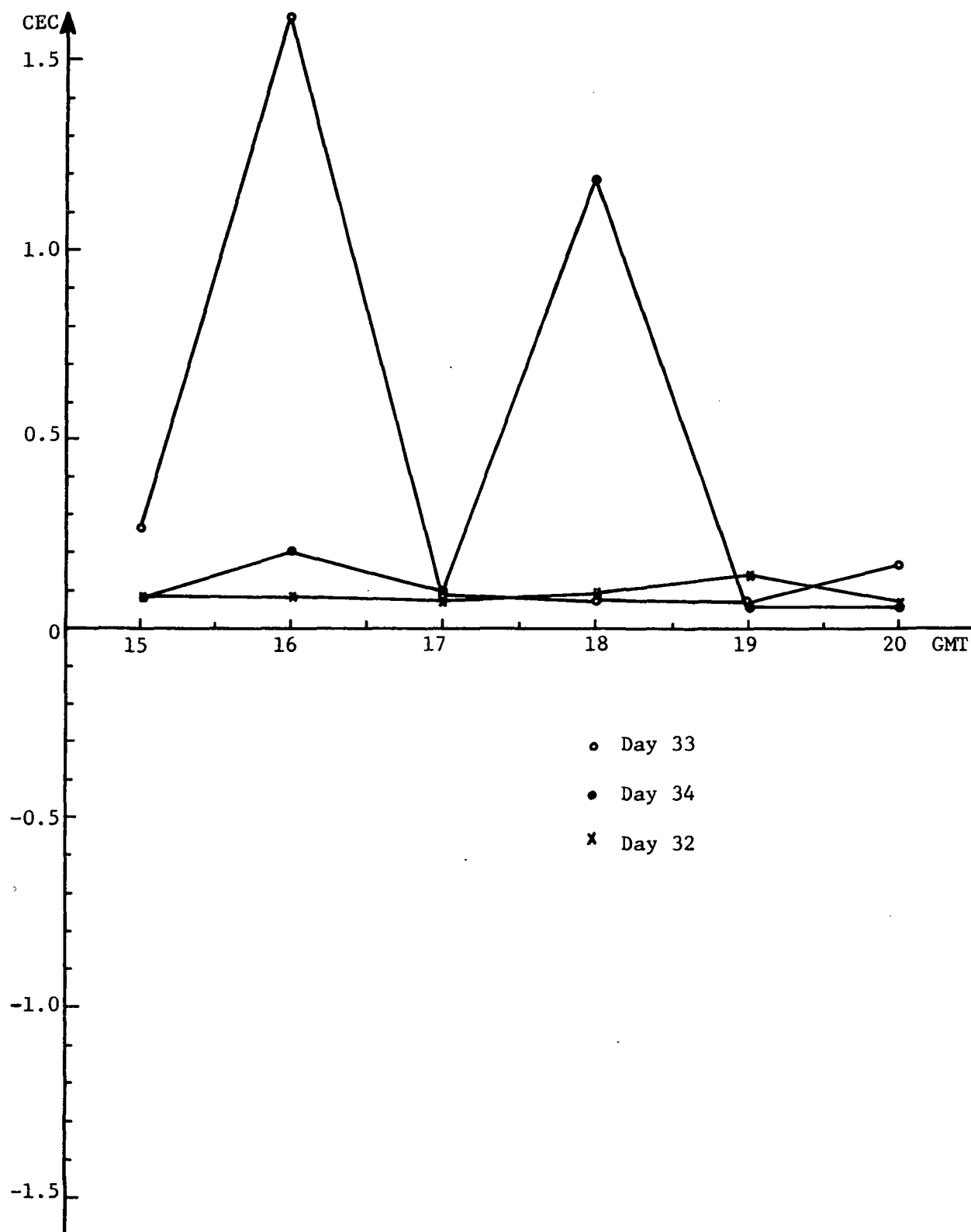


Fig. 6-7. Side-by-side daytime differential error standard deviation vs. time using 5 min averaged samples, 10.2 kHz, B-D LOP, digital PLL receiver, February 1974.

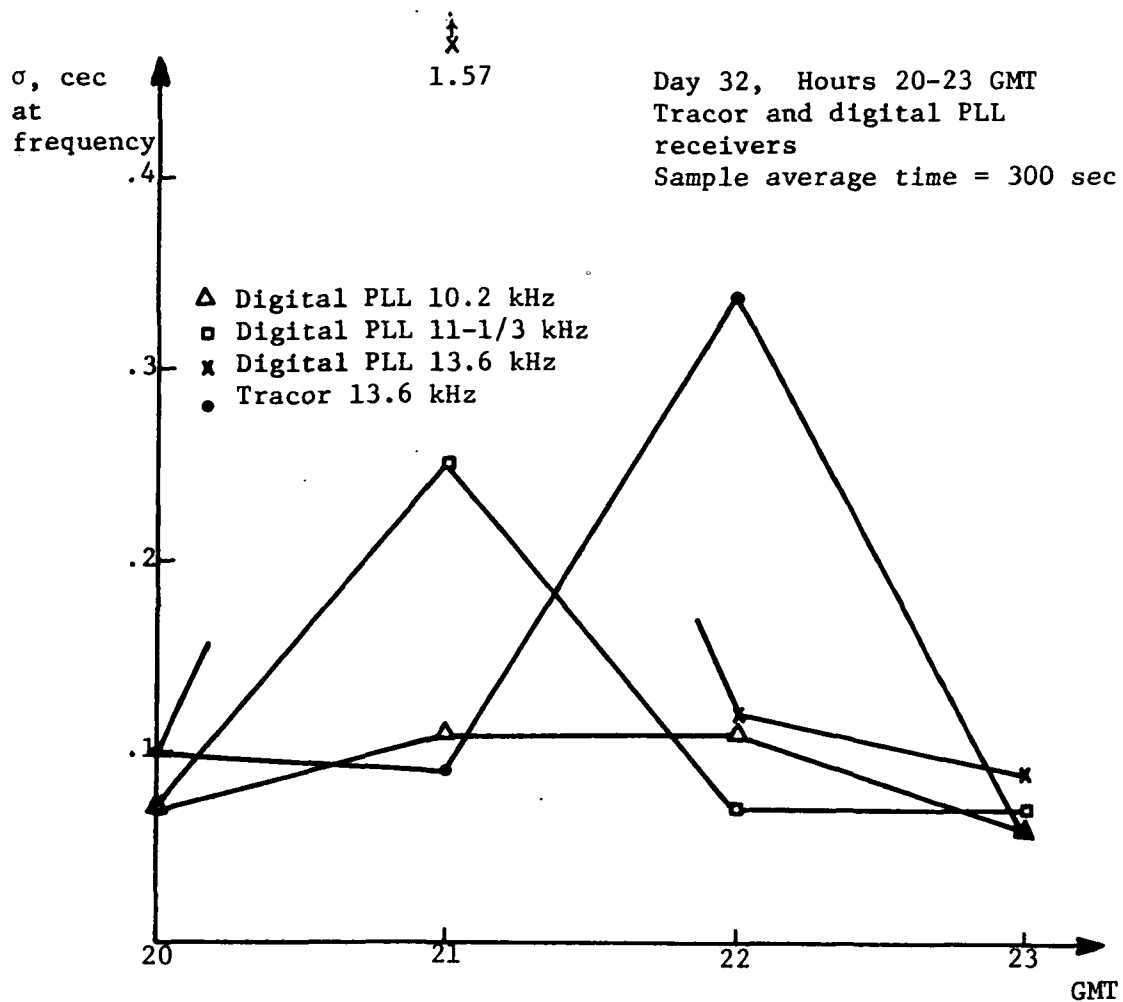


Fig. 6-8. Side-by-side differential error standard deviation, σ , vs. time using 5 min averaged samples during daytime, February 1974; Digital PLL at 10.2, 11-1/3, 13.6 kHz; Tracor at 13.6 kHz.

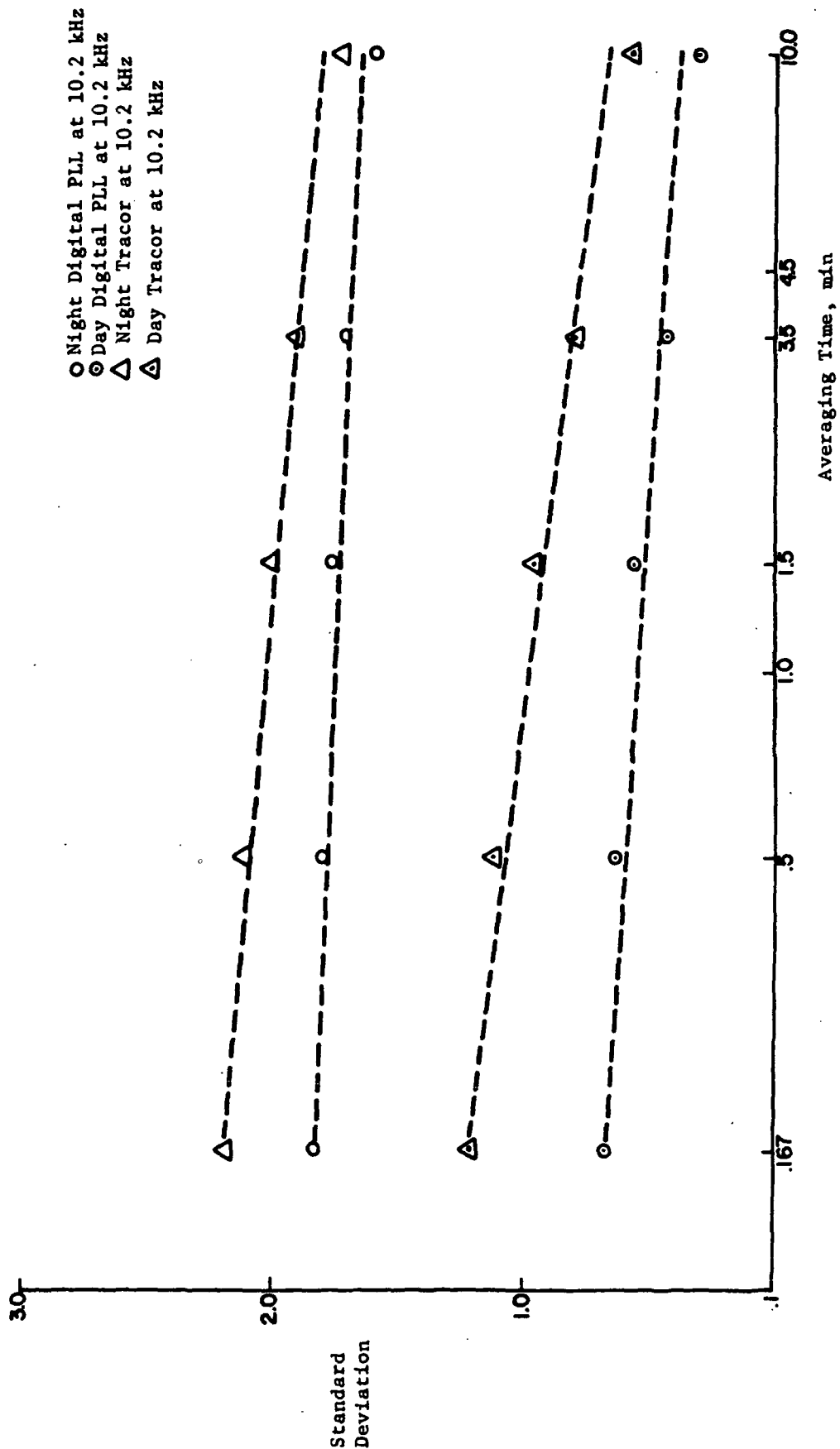


Fig. 6-9. Differential error standard deviation vs. sample averaging time, mobile receiver at Ahoskie, September 1973.

differential error with the remote receiver at Ahoskie, N.C., versus sample averaging time. Day and night variation is presented using both the digital receiver (second order loops) and the Tracor receiver at 10.2 kHz. Again it can be noted that the standard deviation of the Tracor data is slightly greater than with the digital PLL receiver. With ten minute averaging an error standard deviation of approximately 0.30 is shown for the digital receiver and approximately .57 cec for the Tracor receiver. Nighttime variation is approximately 2-4 times greater with less variation with sample averaging time. This indicates that the nighttime uncorrelated variation is at a lower frequency than during the day.

6.3 LOP Measurement Accuracy

With no sample averaging Figures 6-10 through 6-14 provide distributions of uncorrected LOP measurement at Hampton, Virginia during September 1973. Figure 6-10 is a probability density function of four days of B-D LOP data at 11 1/3 kHz. The overall mean is 9.42 relative to the chart LOP value, (see Appendix J) 90.55, at the receiver sites. The overall standard deviation relative to the data mean is 11.8 cec. The daytime values are contained in the mode near the chart value. Nighttime values contribute to the broad mode from about 15-30 cec above the chart value. The remainder of the variation occurs primarily during the transition periods. Figure 6-11 is the modified cumulative probability function for the data of Figure 6-10. In Figure 6-11 the probability of encountering a measured LOP phase less than or equal to some selected value can be read directly. For example, the probability of measuring a phase difference less than or equal to 15 cec is approximately 0.65.

In Figure 6-12 the probability function of the transition period time is given. The distribution is relatively flat. The peak at 30 cec represents the values at 30 cec or above and is not a mode. In Figure 6-13 the daytime values are shown in a density function plot while Figure 6-14 is for the nighttime period. The standard deviation of the nighttime period (5.6 cec) is approximately three times that of the daytime period (1.8 cec).

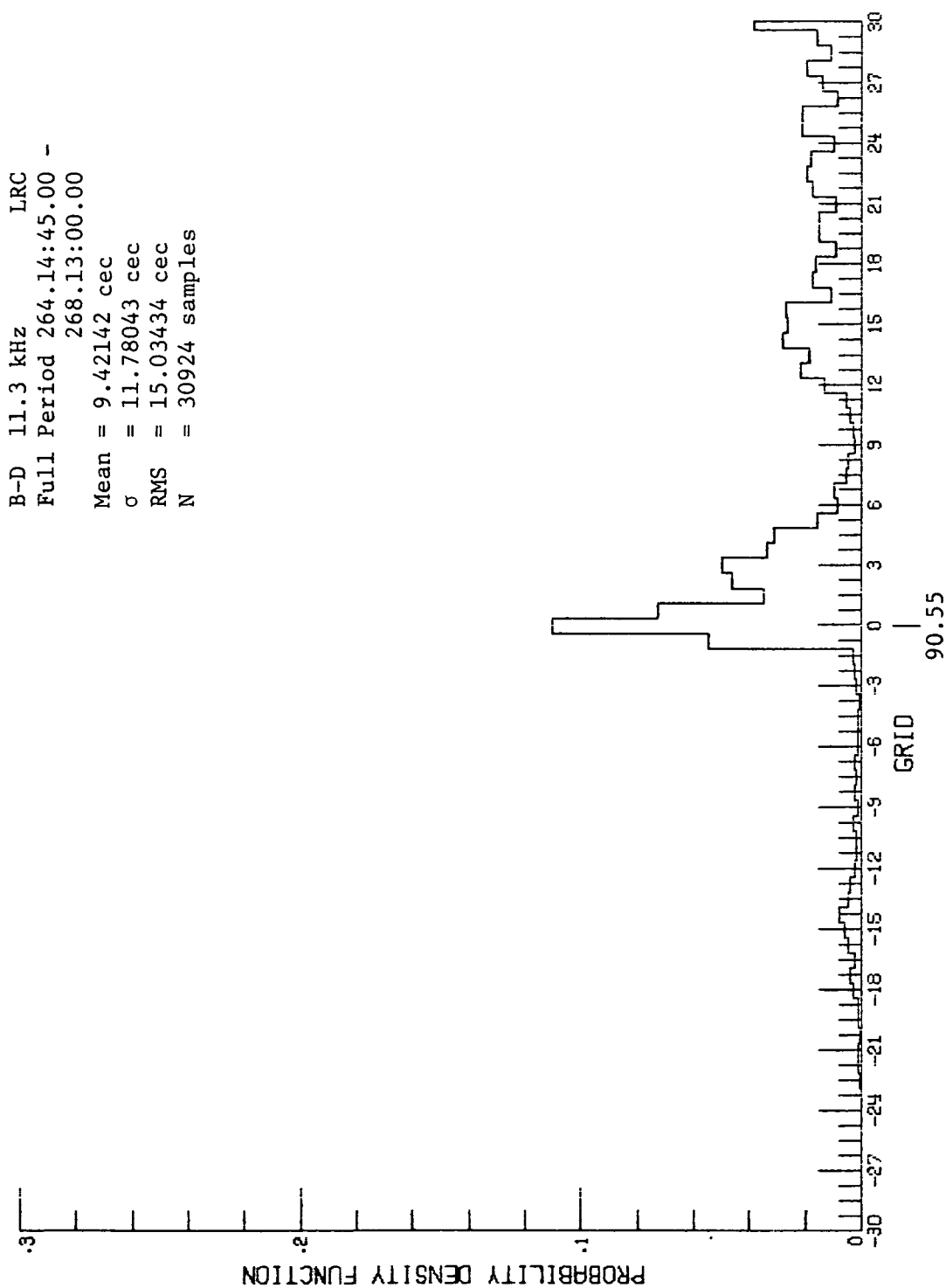


Fig. 6-10. B-D LOP measurement probability density function for 24-hour period at 11-1/3 kHz at Hampton, September 1973, digital PLL receiver.

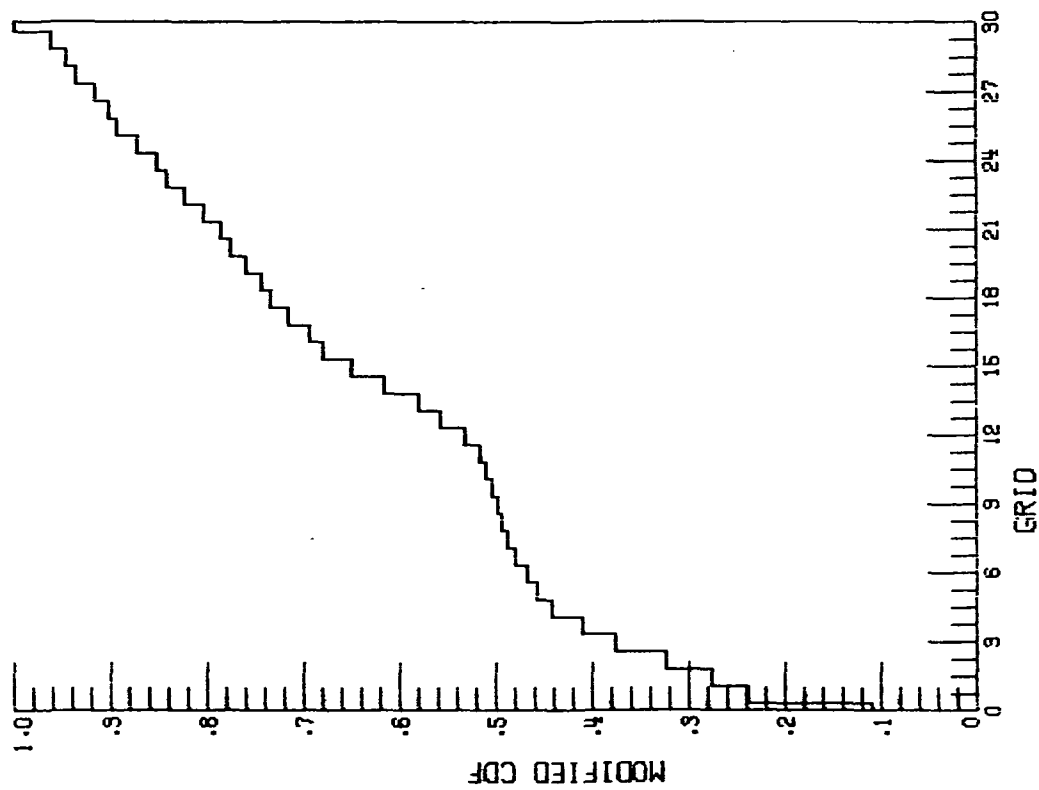


Fig. 6-11. B-D LOP measurement modified cumulative probability density function for 24-hour period at 11-1/3 kHz at Hampton, September 1973, digital PLL receiver.

B-D 11.3 kHz LRC
 Transition Times 2200-0130
 0930-1145
 Day 264-268
 Mean = 11.51849 cec
 σ = 16.45693 cec
 RMS = 20.08664 cec

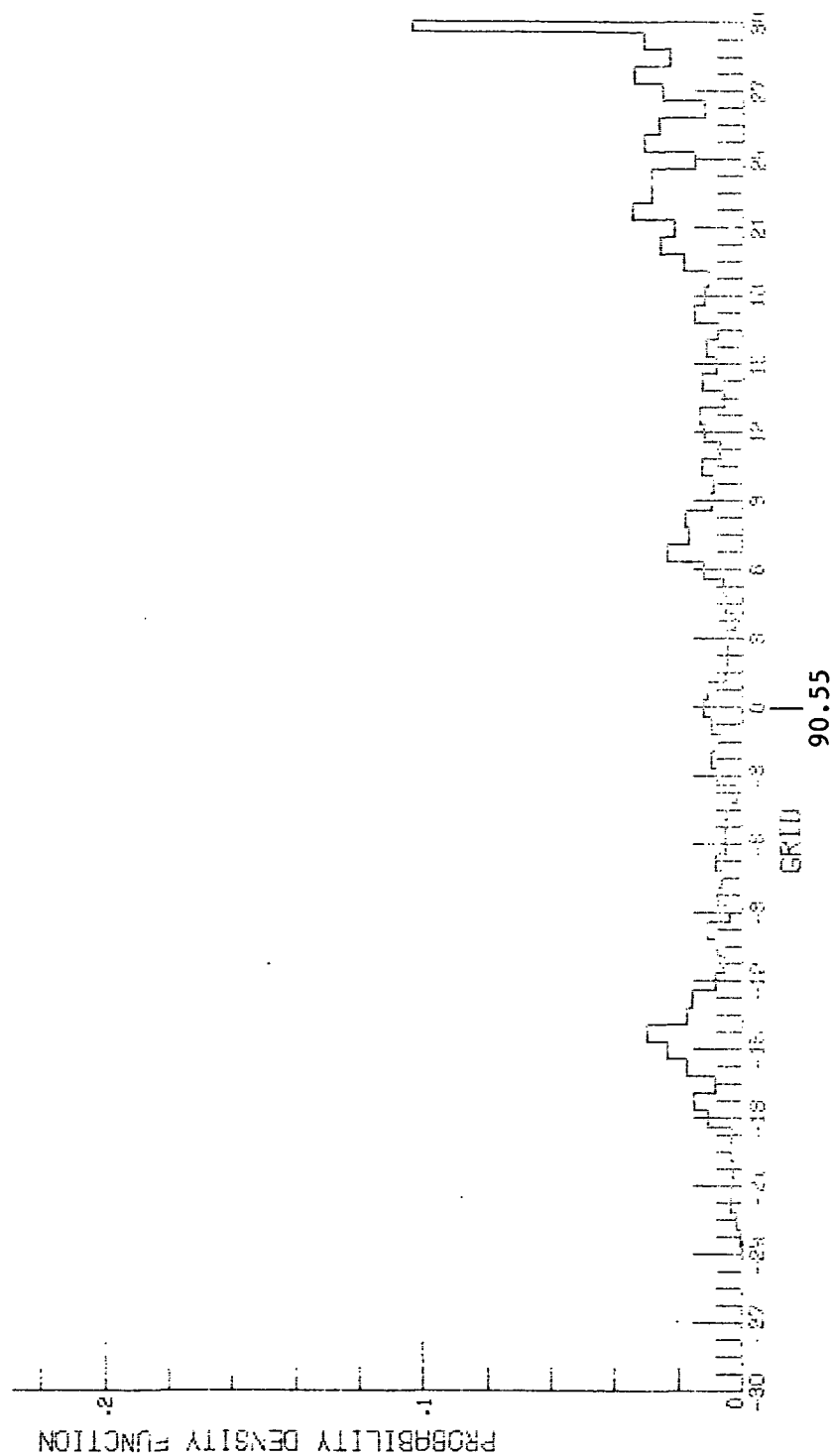


Fig. 6-12. B-D LOP measurement probability density function at 11-1/3 kHz at Hampton during total of transition times, September 1973, digital PLL receiver.

B-D 11.3 kHz LRC
 Daylight 1145-2200
 Day 264-268
 Mean = 1.58799 cec
 σ = 1.86417 cec
 RMS = 2.44880 cec

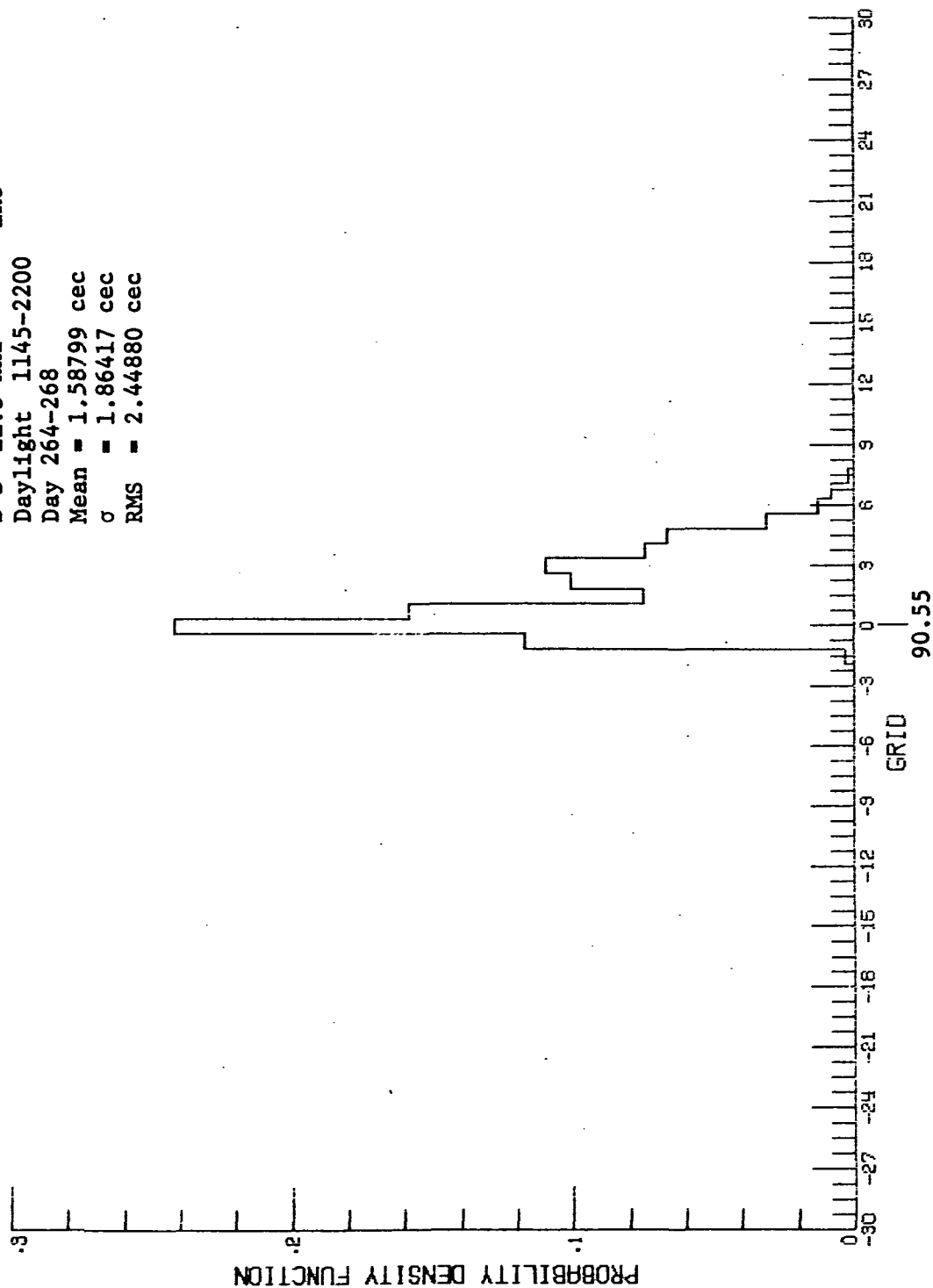


Fig. 6-13. B-D LOP measurement probability density function at 11-1/3 kHz at Hampton during daytime period, September 1973, digital PLL receiver.

B-D 11.3 kHz LRC
 Night 0130-0930
 Day 264-268
 Mean = 19.30635 cec
 σ = 5.56041 cec
 RMS = 20.09104 cec

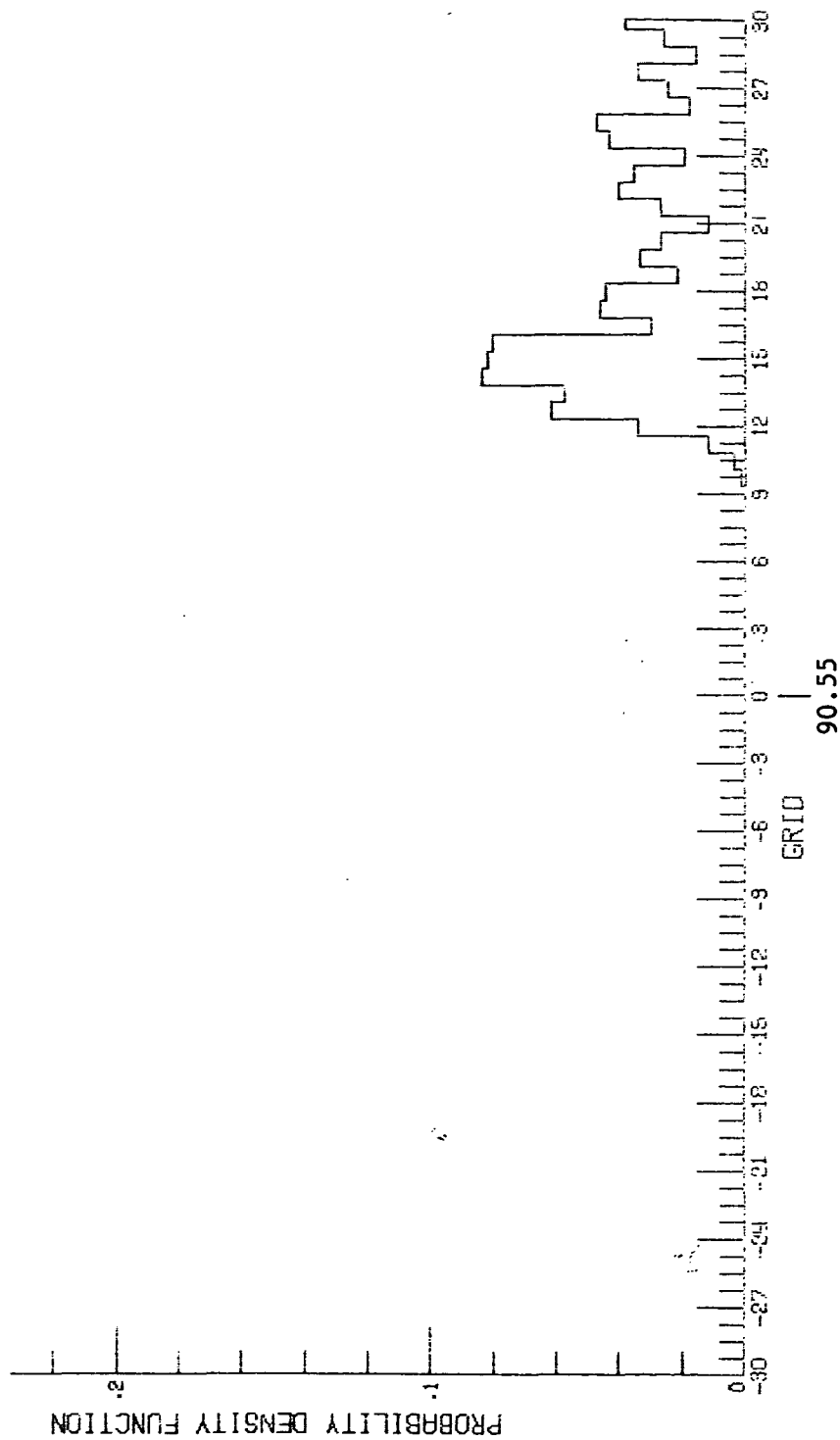


Fig. 6-14. B-D LOP measurement probability density function at 11-1/3 kHz at Hampton during nighttime period, September 1973, digital PLL receiver.

In Figure 6-15 the standard deviation of uncorrected LOP measurement accuracy at 10.2 kHz as a function of sample averaging time is illustrated. The digital PLL receiver (second order loops) and the Tracor receiver compare very closely during the respective nighttime and daytime periods shown. It can be noted that averaging time affects this standard deviation very little (much less than for differential OMEGA error) which indicates that variations are low frequency. The nighttime standard deviation (~3 cec) is on the order of 1.5 times the daytime value (~2 cec) for sample averaging up to 10 minutes. The standard deviation of the 10.2 kHz data is generally greater than for the 11 1/3 kHz data as is the case comparing Figures 6-13 and 6-15.

6.4 Composite OMEGA Analysis

The analysis results relative to the composite mode of operation are limited. Primarily, emphasis has been placed on comparing difference frequency data and fundamental frequency data both with and without skywave corrections.

For Norway-Trinidad data obtained at Hampton during February 1974, the standard deviation of LOP measurement error without skywave corrections is presented in Figure 6-16. In Figure 6-17 this error with skywave corrections is shown, and in Figure 6-18 the affects of 10 min sample averaging is illustrated. All of these values are shown in cec units at 10.2 kHz with separate curves for the full daytime period, full nighttime period, the transition periods (dusk and dawn separately and together) and the full 24 hour period.

Results show that the sample averaging (low pass filtering) offers very little improvement in the difference frequency error. Also skywave corrections actually increase the difference frequency LOP error which indicates a previously observed shortcoming of the corrections. It should also be noted that the errors are small enough to allow for good lane identification capability using a difference frequency without skywave corrections at 10 sec measurement intervals.

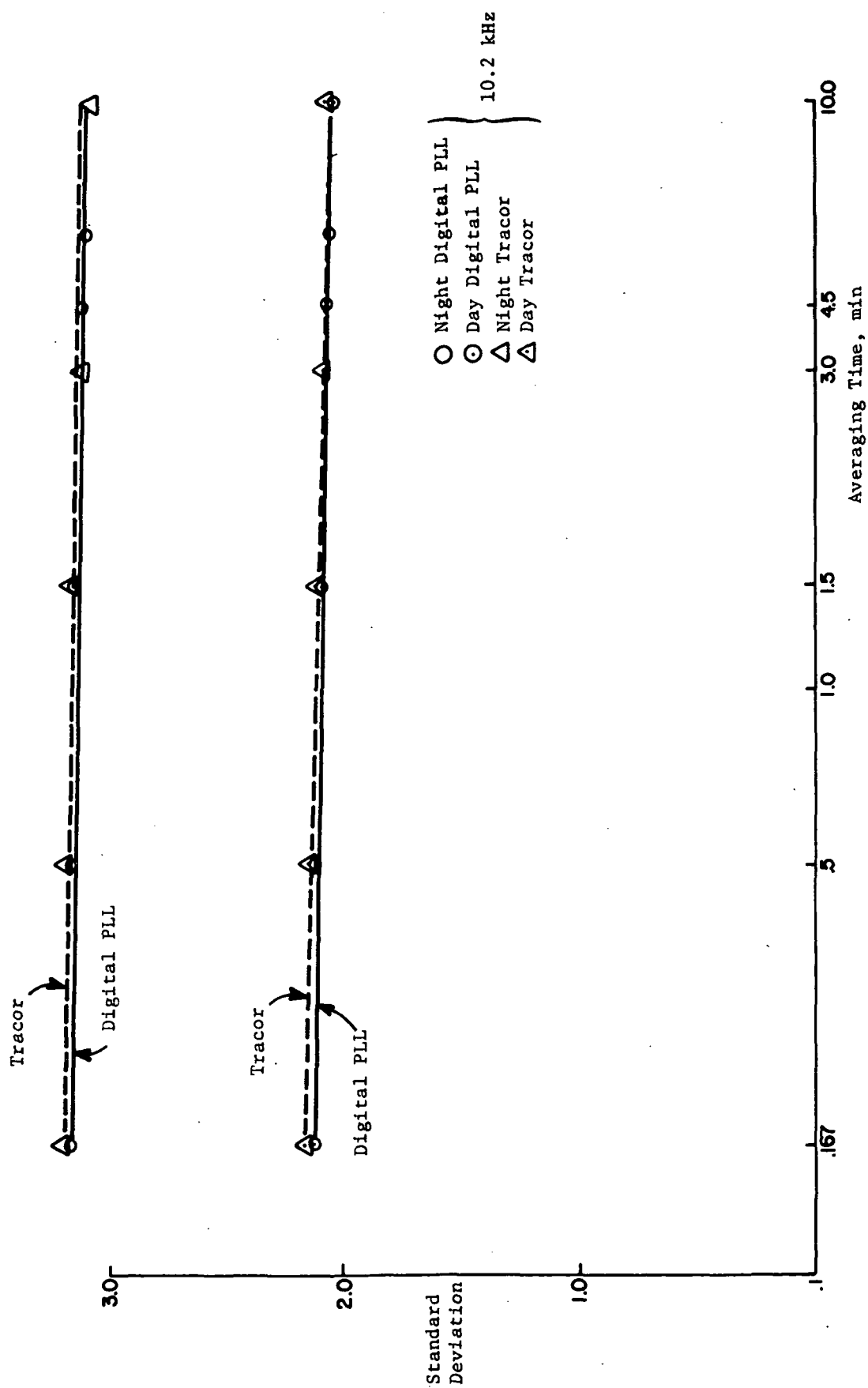


Fig. 6-15. B-D LOP measurement error standard deviation vs. sample averaging time, digital PLL and Tracor 599R receivers at 10.2 kHz at Hampton, Virginia, September 1973.

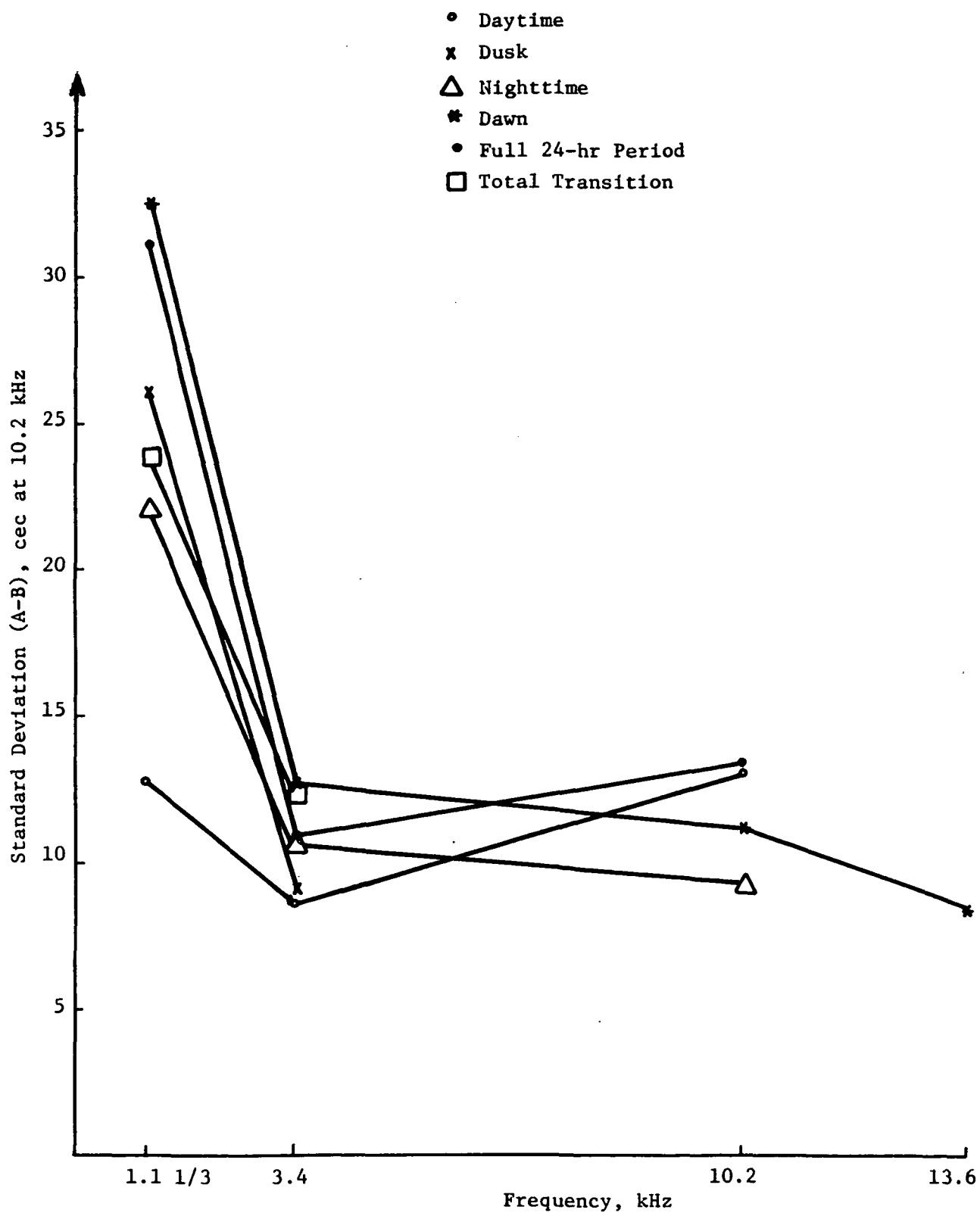


Fig. 6-16. LOP standard deviation at Hampton with no skywave corrections.

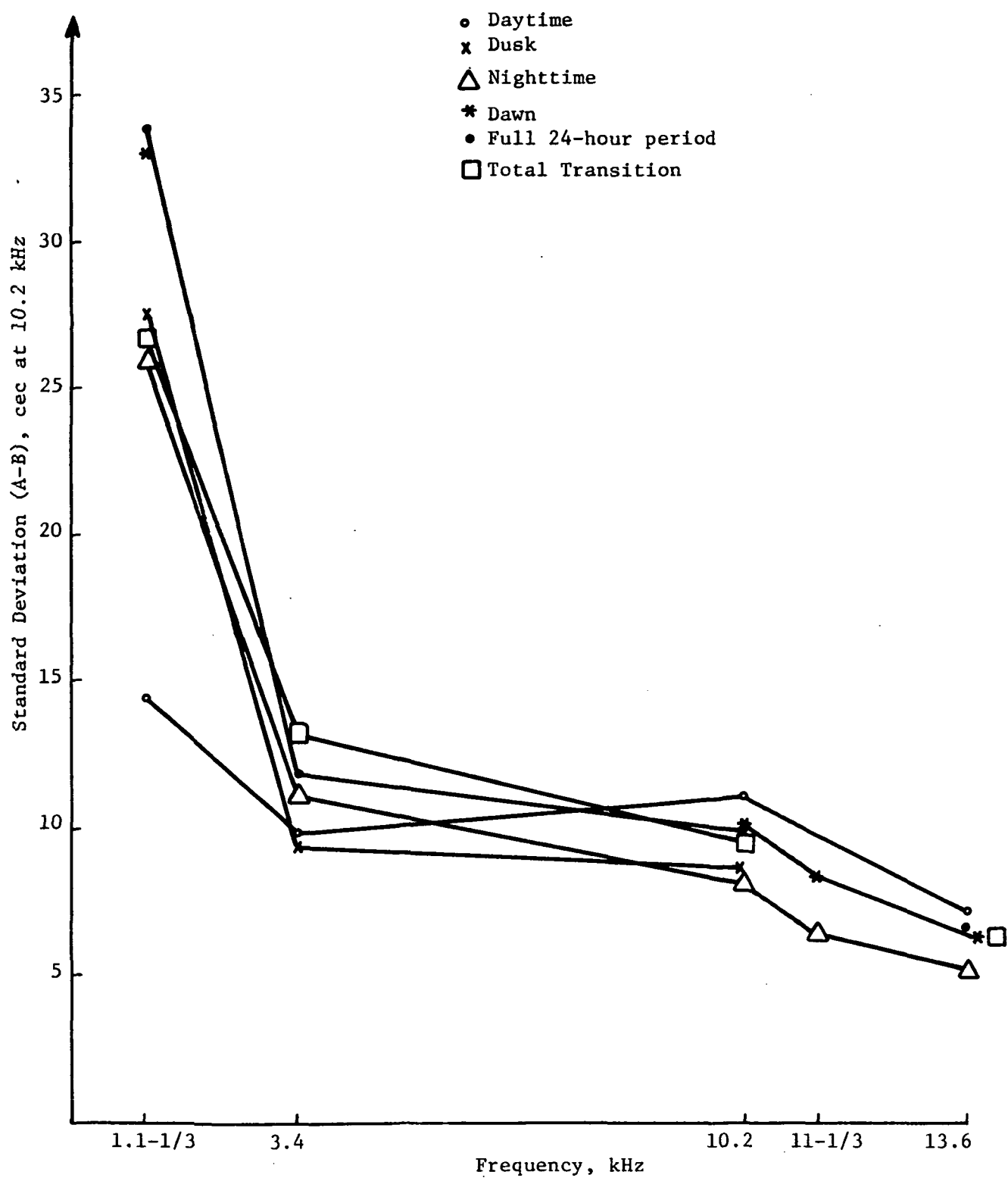


Fig. 6-17. LOP standard deviation at Hampton with skywave corrections.

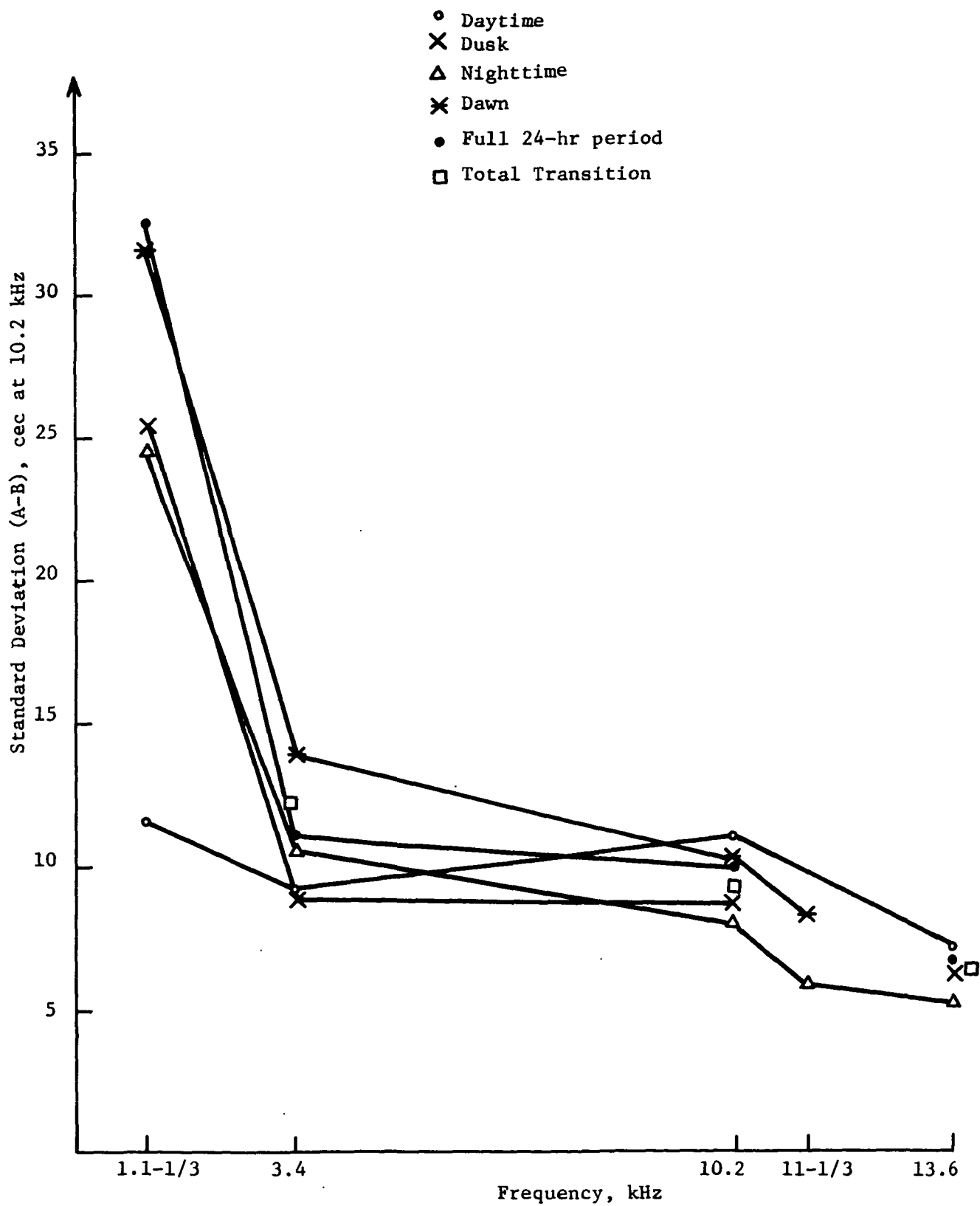


Fig. 6-18. LOP standard deviation at Hampton with skywave corrections using 10 min averaged samples (low pass filtering).

6.5 Results of Regression Analysis

The regression procedure has been used to analyze the daytime period differential OMEGA error mean values from eight base/mobile receiver situations. Differential error is with respect to chart LOP phase difference for any given situation. See Appendix J for tables of chart values used. Specifically, differential OMEGA readings of the B-D LOP were used, which included data taken at seven locations away from Hampton, Virginia, and one series of readings at Hampton. Readings at any one location are five minute means averaged over several days, matched on five minute intervals from 1500 GMT - 2100 GMT. Hence, the data analyzed are an array of averaged (with respect to days within a location), nonoverlapping, five minute means with the chart value difference subtracted. The dimension of the array is 72 x 8; i.e., 72 five minute averages at each of the locations.

Analysis of these data is directed in three general areas: first, the variations within the daytime period for which the data are available (1500 GMT - 2100 GMT); second, the variation of error with respect to remote receiver position; and finally, if this effect is present, the relationship between error and position coordinates is desired.

6.5.1 General Regression Model.-- A general model of the form is postulated

$$\epsilon_D(i,j) = m + t_i + l_j + e_{ij}, \quad (6-1)$$

where,

$\epsilon_D(i,j)$ = the averaged, measured differential error at time period i , ($i = 1, \dots, 72$), and location j , ($j = 1, \dots, 8$);

t_i = the effect due to the i th time period;

l_j = the effect due to the j th location; and

e_{ij} = a random perturbation about the mean function $m + t_i + l_j$.

Hence, firstly, the analysis attempts to test $t_1 = t_2 = \dots = t_{72}$ and $l_1 = l_2 = \dots = l_8$. That is, does ϵ_D , except for random perturbations, behave the same over the 72 time periods and at the 8 different locations?

Secondly, if a location effect is determined, an analysis of the l_j is to be done in order to examine simple relationships among the l_j . Specifically, by least squares fitting, an attempt is made to investigate the possibility of explaining the location effects by simple functions of range (from Hampton) and azimuth (relative to true North).

6.5.2 Regression Analysis Results.— In order to assess the variability of the differential OMEGA readings with respect to location and time effects as specified in the model (6-1), an analysis of variance procedure was performed. As in regression analysis, the outputs of an analysis of variance procedure are sums of squares of the observations, certain ratios of which may be used to test various hypotheses concerning the underlying process or model. Now, the appropriate ratios to be used depend upon the nature of the effects, whether they are "fixed" or "random," and on the correlation structure of the data. For the experimental situation which is of concern here, the effects are fixed. That is, neither the locations nor the time periods were chosen by a chance mechanism; hence, the correlation structure of the data will determine the appropriate ratios to be used.

To determine the presence and magnitude of the correlation between the five minute averages, the five minute averages were, themselves, averaged over the eight locations. A linear time trend was then estimated and the first order autocorrelation of the residuals was calculated. The autocorrelation was estimated at $\hat{\rho} = -.058$, an extremely small value. Hence, it was assumed that the correlation of the five minute averages was negligible and the appropriate "error" sum of squares would be calculated simply as the squared deviation of the 576 observations from their predicted values.

Next an analysis of variance procedure was performed to assess time and location effects. The results are presented in Table 6-1.

From Table 6-1 it is seen that there is very little difference among the 72 time periods and there are substantial differences among the locations; differences among the locations account for $100 \times (119.888/167.052) = 71.8\%$ of the total variation of the data.

Table 6-1

Analysis of Variance			
Source of Variation	Degrees of Freedom	Sum of Squares	Significance Level
Locations	7	119.888	0.0001*
Time Periods	71	4.939	0.8508
Error	497	42.225	
Total	575	167.052	

*Highly significant

Having determined that there are, in fact, differences among the locations, an attempt is made to explain these differences in terms of their geographic coordinates.

For this analysis, means over time periods within locations are used. It should be noted that this averaging, due to the equal number of observations represented in each location mean (72), results in the same "fits" on the geographic coordinates as would occur if we did not average. These means are given in Table 6-2.

Table 6-2
Location Means

<u>Location</u>	<u>Range</u> <u>n.mi.</u>	<u>km</u>	<u>Azimuth</u>	<u>\bar{d}</u>
LRC	0	0	Undetermined	-0.883
FEU	11.243	20.82	286.359	-0.217
FIS	19.854	36.77	90.750	+0.036
PGO	40.042	74.16	277.369	-0.331
AHO	56.895	105.37	213.200	-0.916
WAL	66.001	122.23	40.840	-1.313
BDF	151.757	281.05	280.460	-0.030
NCC	101.258	187.53	347.430	-0.238

For computational and geometric considerations, the following transformation on azimuth was made:

$$TH = (AZIMUTH - 46.25) \times \left(\frac{\pi}{180} \right).$$

Hence, the coordinates were converted to radians and rotated to coincide with the B-D LOP through the base receiver. The B-D LOP at the base receiver is 46.25° east of true north.

Now, preliminary plotting suggested that ϵ_D was periodic in TH, with period π . Hence, several functions of the form:

$$\epsilon_D = \alpha + \beta f(R, TH) ,$$

where

R = range

TH = angle (defined above),

were fitted to the means by the use of regression analysis. Summary statistics for all the fits are given in Table 6-3.

From Table 6-3 it is seen that the functions with period π tend to fit well while functions with period 2π are uniformly poor. Also, from the last 12 fitted functions given in Table 6-3, it is seen that changing the periodicity in the neighborhood of π and smoothing the response function by using "non-rectified" trigonometric functions does not yield improved fits to the data.

6.5.3 Conclusion.-The analyses performed tend to support the concept that the differential reading is reasonably stable over the hours 1500 GMT - 2100 GMT.

The data also strongly suggest that the position of the mobile receiver does affect the differential error. And, by the analyses of the location means, the data suggest that the response varies by the coordinates of the position of the mobile receiver (as opposed to "local" phenomena) and that the means have period π as measured as a function of the variable TH.

However, certain shortcomings in the available data are apparent. Specifically, there is an insufficient spread and number of both the ranges and azimuths chosen; a greater spread in these variables would give a greater sense of confidence in the inferences made.

The shortcomings are manifested if one takes note of the following two functions which were fitted and summarized in Table 6-3.

A function which fits especially well is:

$$\hat{\epsilon}_d = -1.317 + 1.433 |\sin(\text{TH})|.$$

Using this function, 85.3% of the variation among the 7 non-Hampton means can be explained, 76.1% of all 8 means can be explained, and 54.6% of the total variation can be explained.

This function is plotted along with the 7 non-Hampton means in Figure 6-19.

Table 6-3

Summary of Location Mean Fits

Total Sum of Squares	167.0525	Degree of Freedom 575
Sum of Squares Error + Time Periods	47.2250	568
Sum of Squares Locations	119.8885	7
	% of Variation Among Means	% of Total Variation
Locations	100.0	71.8
Fitted Function		
sin(TH)	5.0	3.6
cos(TH)	2.3	1.6
sin(TH)-cos(TH)	0.08	0.05
sin(TH)	76.1	54.6
cos(TH)	63.5	45.6
sin(TH) - cos(TH)	71.7	51.5
R sin(TH)	21.0	15.1
R cos(TH)	10.1	7.2
R(sin(TH) - cos(TH))	1.1	7.2
R sin(TH)	28.6	20.5
R cos(TH)	1.2	0.8
R(sin(TH) - cos(TH))	68.4	49.1
sin(1.9TH)	38.7	27.8
sin(2TH)	27.7	19.8
sin(2.1TH)	20.1	14.4
cos(1.9TH)	49.3	35.4
cos(2TH)	68.4	49.1
cos(2.1TH)	61.7	44.3
R sin(1.9TH)	22.2	16.0
R sin(2TH)	13.7	9.8
R sin(2.1TH)	8.2	6.0
R cos(1.9TH)	32.6	23.4
R cos(2TH)	65.7	47.1
R cos(2.1TH)	55.2	39.6

STATISTICAL ANALYSIS SYSTEM

Plot of: $\bar{d} = -1.317 + 1.433 |\sin(\text{TH})|$

● = Location Mean

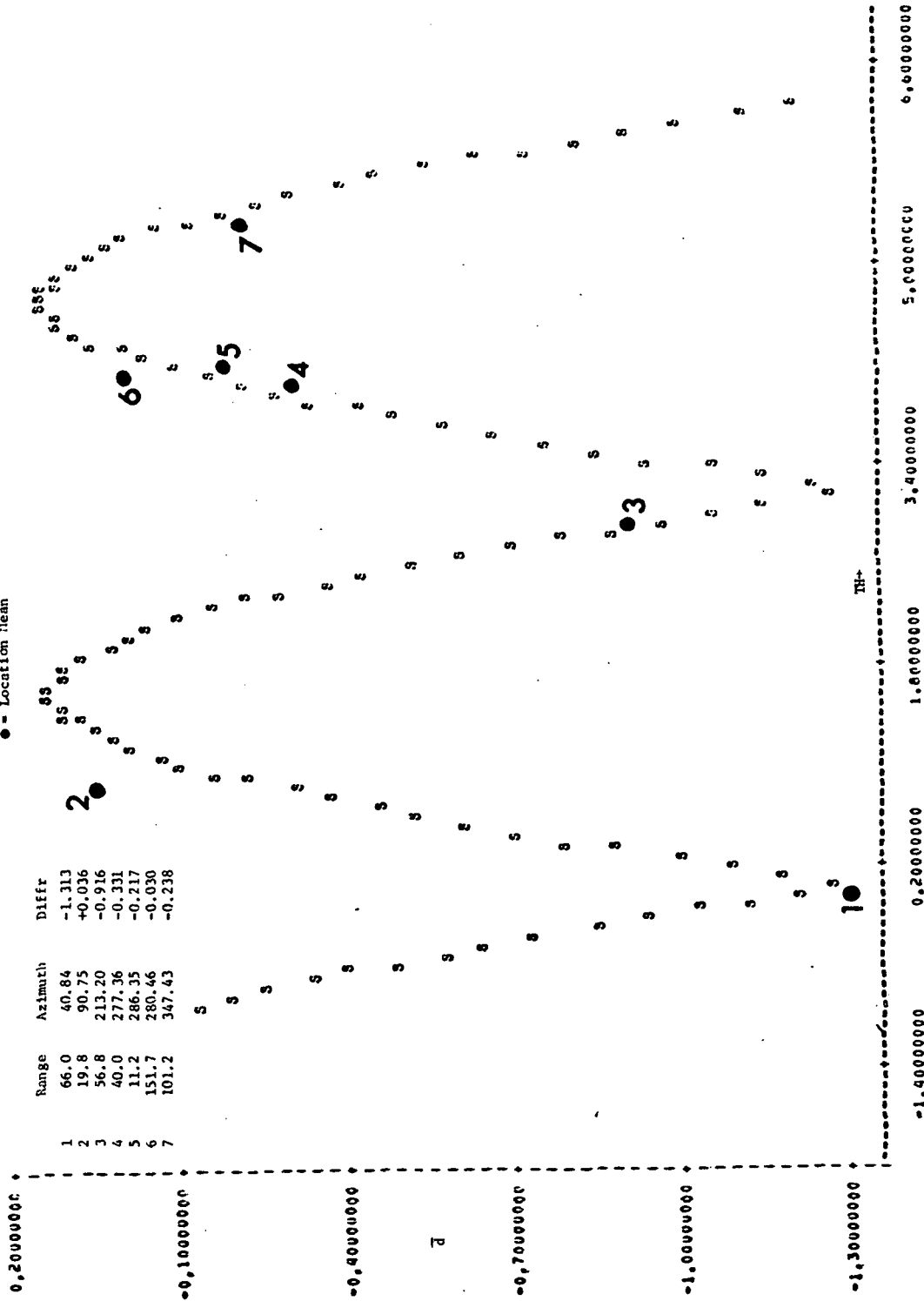


Fig. 6-19. Differential error mean (\bar{d}) vs. relative azimuth (TH).

Plot of: $\bar{d} = -.476 - .0099 r \cos(2TH)$
 ● = Location Mean

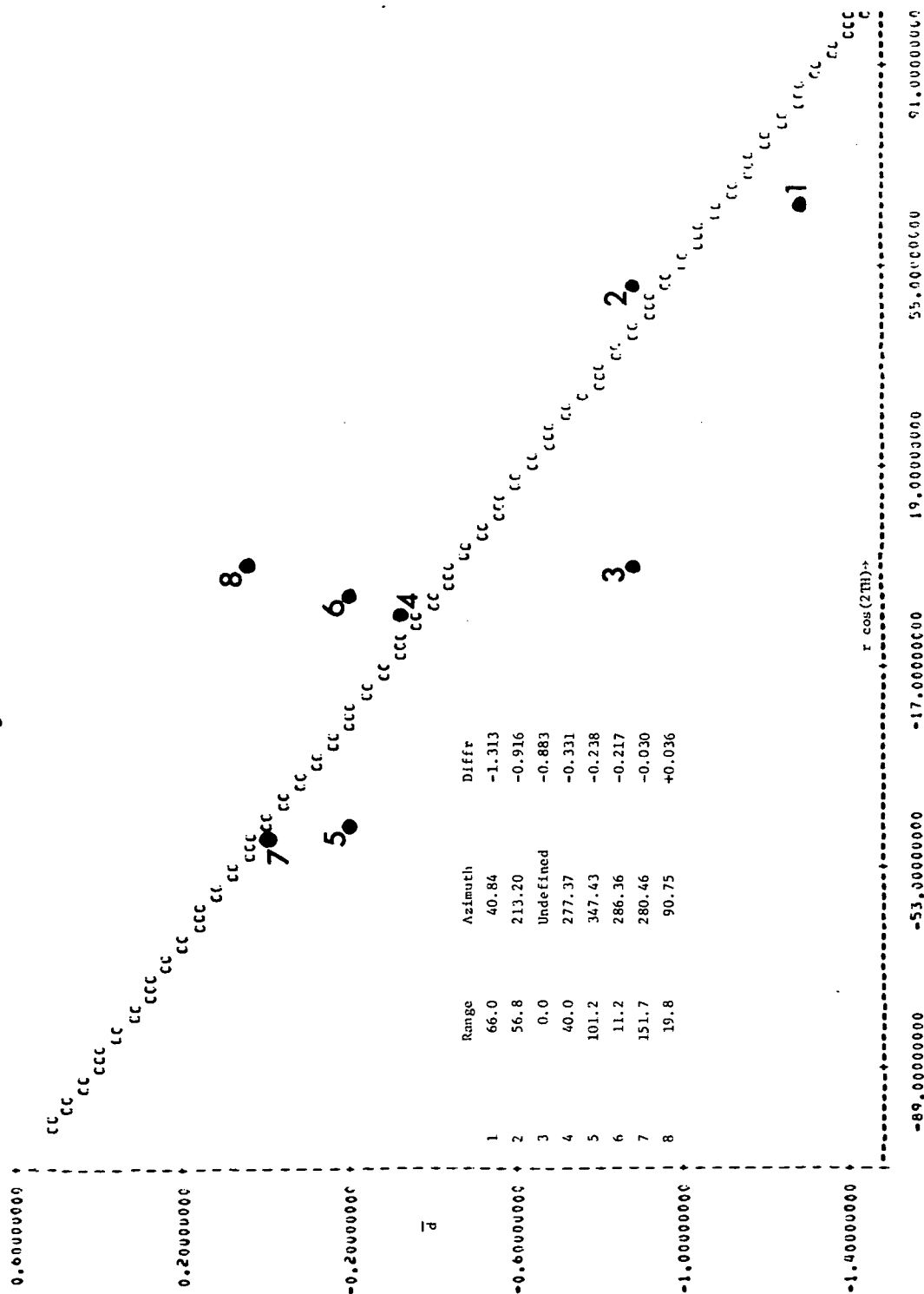


Fig. 6-20. Differential error mean (\bar{d}) vs. $r \cos(2TH)$ where r is receiver separation and TH is relative azimuth.

In Figure 6-20, the function

$$\hat{\epsilon}_d = -.478 - .0099 R \cos(2TH)$$

is plotted along with all 8 location means. For this function, the percent of variation explained is 65.7% among the variation of the 8 means and 47.1% of the variation of the entire data set.

In terms of the percentage of the variance explained, one would conclude that either of the functions fits the data well. However, upon inspection of Figure 6-19 it is seen that 4 of the 7 plotted means are, in terms of the variable TH, clustered very close to each other, giving reduced confidence in inferences made over the entire range of TH. Also upon inspection of Figure 6-20 4 of 8 of the plotted means are within a very short distance of each other when measured on the $R \cos(2TH)$ scale, again pointing out the limitations of the data in providing information with respect to the association of response variability and position coordinates.

6.6 Summary

Results presented indicate that LOP type differential error standard deviations as low as 0.25 cec at 10.2 kHz are entirely conceivable without the use of skywave corrections. This is to a large extent an inherent error based on the receiver analysis provided. The regression analysis results tend to support that the mean error is largely predictable and is primarily a function of the azimuth between receivers and not on the separation range for separations under 150 n.mi. (277.80 km).

Future analysis of the extended data set, to be obtained, will offer results from which more confident conclusions can be made. The inclusion of additional parameters will provide for a more complete explanation of the variations observed in the OMEGA data.

CHAPTER 7

RECOMMENDATIONS FOR AIRBORNE TESTS

7.1 General

As mentioned previously in this report the results presented here have been preliminary in the sense of an extensive analysis of differential OMEGA error. More exhaustive results will be possible after completion of the current ground based test plan. The experience gained thus far and published results from previous airborne tests provide an intelligent basis for recommendations concerning the design and execution of airborne OMEGA tests to follow. Currently, NASA Langley personnel plan to flight test a Bendix Corporation developed differential OMEGA system in coordination with the FAA which procured the system.

7.2 The Airborne Equipment

In the airborne test program the Bendix differential OMEGA receiver will be used to evaluate the utility of this mode of operation for aviation navigation. The system consists of two OMEGA VLF receiver units each including a second order phase-locked loop receiver, a digital computer, and terminal equipment to provide a data link between the receiver units. The airborne unit will also have a digital magnetic tape recorder to record the OMEGA phase data. A velocity aiding algorithm will be available within the airborne computation system.

Computer software used in data analysis of the ground based OMEGA tests will be directly applicable for evaluation of the airborne system. It will be necessary to reformat the recorded data from the Bendix system to gain compatibility with existing software. Analysis is provided for uncorrected and skywave corrected relative phase and LOP phase differences for all possible pairs at ten second intervals. Single receiver tapes used to evaluate LOP measurement accuracy and merged receiver tapes used for side-by-side analysis and differential accuracy analysis will be prepared in the packed binary format compatible with the software provided for the CDC-6600 system.

7.3 Recommendations for Experimental Plan

As the schedule of data accumulation on the ground based experimental plan is completed these analysis results will be needed to assist in final design of the airborne tests. In the airborne tests essentially all the parameters affecting navigation accuracy in the ground based tests will be relevant. Local environmental effects should not be significant aboard the aircraft but additional parameters must be considered, including:

1. Receiver time constants and loop averaging time,
2. Data averaging time,
3. Differential update rate, and
4. Aircraft accelerations.

Having previously determined OMEGA error sensitivity to those parameters which affect the ground based operation, i.e., receivers in a stationary configuration, it should be possible to more readily evaluate the effects peculiar to the airborne operation. Primarily because of receiver/antenna motion and velocity of this motion with respect to the OMEGA transmission, rate error incurred due to limitations on loop averaging time, data averaging time, and update rates can be more significant in attaining desirable navigation precision in an airborne environment. Additionally, aircraft accelerations require that some means of velocity aiding will be necessary to reduce the phase-locked loop receiver error (see ref. 33). The resulting experimental plan should be designed to encompass these additional factors.

In conjunction with development of the necessary parameter considerations on which to base a test plan, aircraft antenna configuration should be investigated. For example, in ref. 34 there is some background information and analysis of several antenna configurations including the blade antenna and crossed ferrite loop antenna with consideration given to antenna placement aboard the aircraft. The complex electronic and electrical systems used on modern aircraft demand that great care be taken to prevent interference from on-board locally generated noise. An added consideration in antenna selection is the susceptibility of the antenna to precipitation static. This is wide-band corona discharge noise which can be potent on high-speed vehicles.

In designing flight tests the actual area in which the tests will be conducted must be selected with due consideration given to the availability of other navigational means. A tracking radar such as the MPS-19 system available at NASA-Wallops would be a prime candidate to provide an alternate position fixing means on which to base the OMEGA navigation accuracy results.

The scheme for selecting basic flight paths should be based on obtaining statistically valid results from data analysis much the same as in designing the ground based tests (Chapter 2). Confidence in analysis results is directly relatable to the adequacy of the data plan to cover the full range of individual variables. Thus the plan should be flexible so that additional data can be gathered as needed as the plan and associated data analysis progress.

With respect to the receiver equipments used in the flight tests it is recommended that extensive laboratory tests be conducted to determine the magnitude of inherent system error. Comparison of the ground station receiver and the airborne station receiver phase measurement should be made to determine the repeatability of these receivers. With the system provided, a direct connection of the two receivers can be used so that a correction channel output applied to the airborne unit phase measurement can supply this output directly. Computer simulation studies such as those presented in Appendix D can prove useful in this evaluation.

A final recommendation concerns the direct usefulness of the present OMEGA receivers used in the ground based tests. Considerable experience has been gained with these equipments and the receiver repeatability and tracking error will be quite well understood at the completion of the present experimental program. These receivers could prove a valuable addition to the airborne tests and it is highly recommended that provision be made to include these equipments. The two major problems to be overcome will probably be the antenna configuration and adaptation of the power supply. These should be relatively minor and the advantages of using these equipments should be the deciding factor.

APPENDICES

APPENDIX A

STATISTICAL DECORRELATION ERROR IN DIFFERENTIAL OMEGA

In defining the error associated with differential OMEGA, some of this error occurs even though propagation paths to each receiver are highly correlated and some is attributed primarily to ionization irregularities and is termed statistical decorrelation error.

Let $\Delta\phi_B$ be the LOP measurement at the base station for a selected pair of transmissions. Let $\Delta\phi_R$ be the LOP measurement of the same pair of transmissions at some remote site within the conventional differential region. Let ϕ_B and ϕ_R be the chart value of the respective LOP's taken as the true value here. The differential error can then be calculated as

$$\varepsilon_D = (\Delta\phi_B - \phi_B) - (\Delta\phi_R - \phi_R) . \quad (A-1)$$

Some of the error in (A-1) can be attributed to the fact that the paths between each transmitter and each receiver are not exactly the same length. Since the receiver separation is small compared to the separation of the receiver area from the transmitters, this error should be small and would be predictable assuming the uniform phase velocities over each transmitter receiver area path. Other components of this error would be basically attributable to differences in the respective transmitter to receiver area paths and to dispersion error when operation is without skywave corrections.

In addition, a portion of this error will be random because of ionization irregularities which will contribute to time varying differences between propagation velocities over the transmitter-receiver paths.

In ref. 27, Kasper used statistical analysis techniques and autocorrelation functions on a large volume of recorded OMEGA data to describe the spatial correlation of OMEGA error. Assuming a stationary process, one of the autocorrelation functions heuristically derived is

$$R_{\Omega}(\Delta x) = \sigma_{\Omega}^2 e^{-|\Delta x|/1500} \quad (A-2)$$

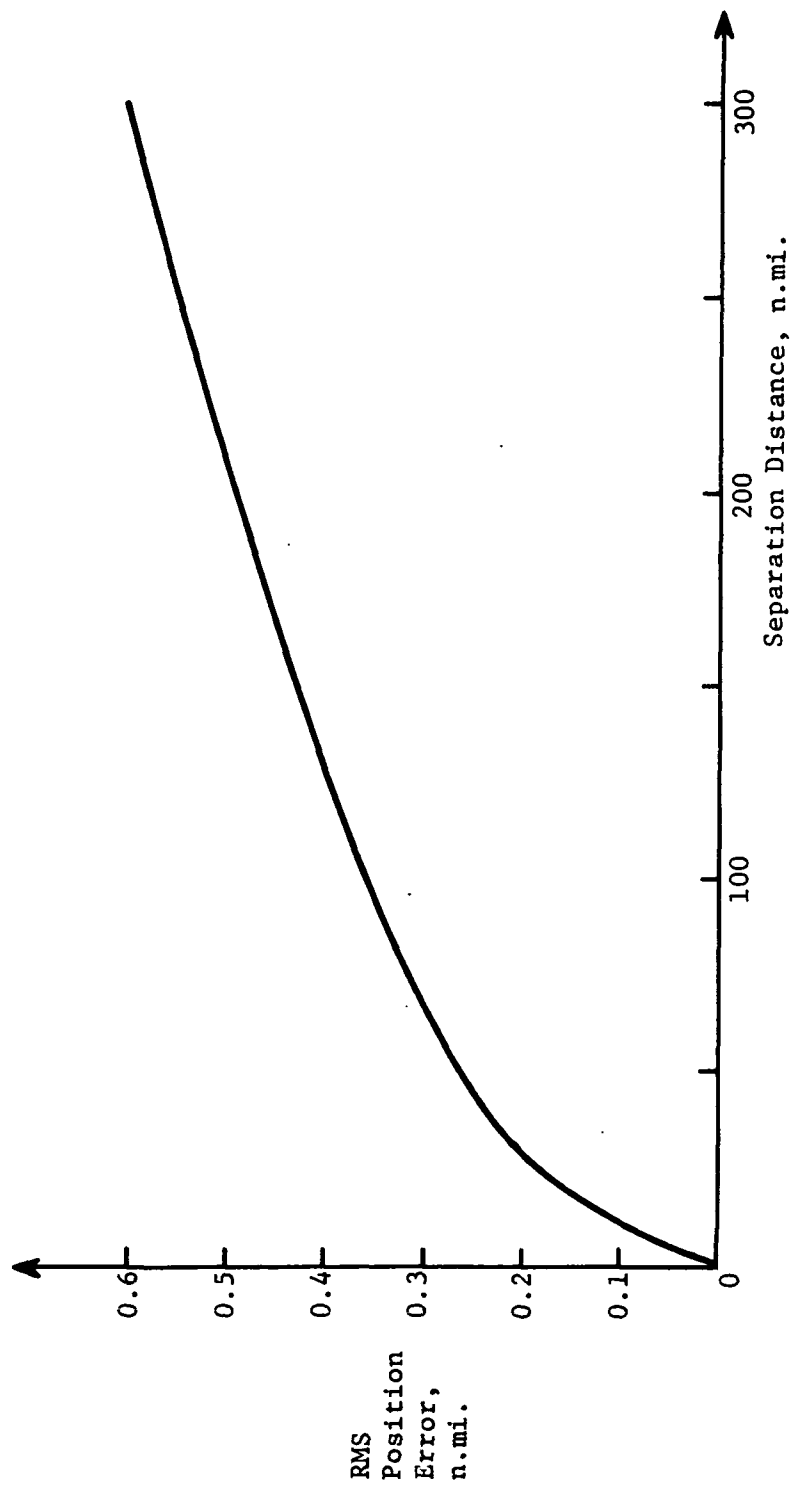


Fig. A-1. RMS differential OMEGA decorrelation error (ref. 27).

where Δx is receiver separation and σ_{Ω}^2 is the variance of the error at a given location. The $R_{\Omega}(\Delta x)$ in (A-2) is an autocorrelation defined as

$$R_{\Omega}(\Delta x) = E \{ \delta\phi(x) \delta\phi(x + \Delta x) \} \quad (A-3)$$

where $E\{\cdot\}$ is the expected value operator and $\delta\phi(x)$ is the uncorrelated OMEGA phase error at receiver position x and $\delta\phi(x + \Delta x)$ is the uncorrelated OMEGA phase error at receiver position $x + \Delta x$ where Δx is the receiver separation. Evaluating (A-3) for all Δx yielded an expression shown in (A-2).

Consider the base receiver at position x_0 and the user or remote receiver at position x . After correction the uncorrelated differential OMEGA error is

$$\varepsilon_D'(x) = \delta\phi(x) - \delta\phi(x_0) \quad (A-4)$$

Calculating the rms error of (A-4) where

$$[\varepsilon_D'(x)]^2 = [\delta\phi(x) - \delta\phi(x_0)]^2$$

and defining the rms error as

$$[E\{[\varepsilon_D'(x)]^2\}]^{1/2}$$

and using (A-2) then

$$\varepsilon_D'(\text{RMS}) = \sigma_{\Omega} (2 - 2e^{-|\Delta x|/1500})^{1/2} \quad (A-5)$$

where Δx is in n.mi. If σ_{Ω} is set to 1 n.mi. (1.85 km) then a plot of (A-5) for receiver separations up to 300 n.mi. (555.50 km) from the base receiver can be made as in Figure A-1. Note that for receiver separations within 200 n.mi. (370.40 km) of the base receiver the rms decorrelation error is less than 0.5 n.mi. (.93 km) without consideration for inherent receiver errors.

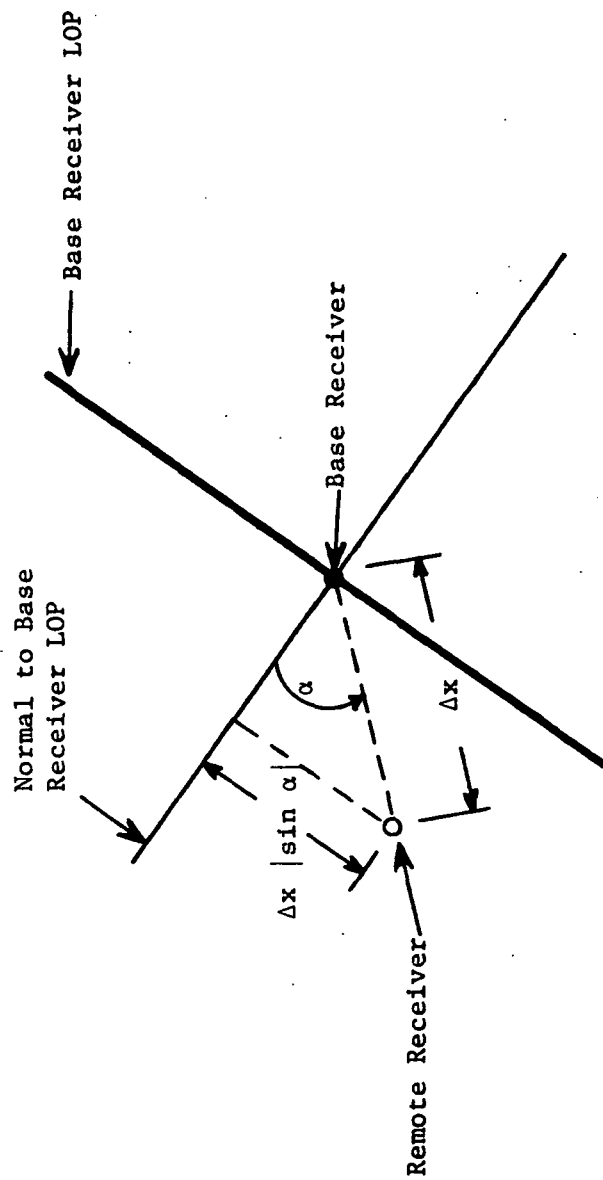


Fig. A-2. Effective decorrelation error separation distance for a given base receiver LOP and given Δx .

Assume that this decorrelation error is not only a function of receiver separation but is also a function of the azimuth of the separation line with respect to the LOP measured. Angular variation is assigned so that this decorrelation error is maximum for receivers separated along a given LOP and minimum along a line perpendicular to this LOP. This is a result of arguing that decorrelated errors are more likely to appear when paths from a given transmitter to each receiver are more dispersed than when they are essentially identical except for the short distance difference within the receiver area.

Assigning a variation of $\sin\alpha$ where α is the angle between the LOP perpendicular and the receiver pair baseline as illustrated in Figure A-2, the rms decorrelation error becomes

$$\epsilon_D'(RMS) = \sigma_\Omega |\sin\alpha| [2 - 2e^{-|\Delta x|/1500}]^{1/2} .$$

This equation is plotted in Figure A-3 for various values of α and can be directly compared to Figure A-1.

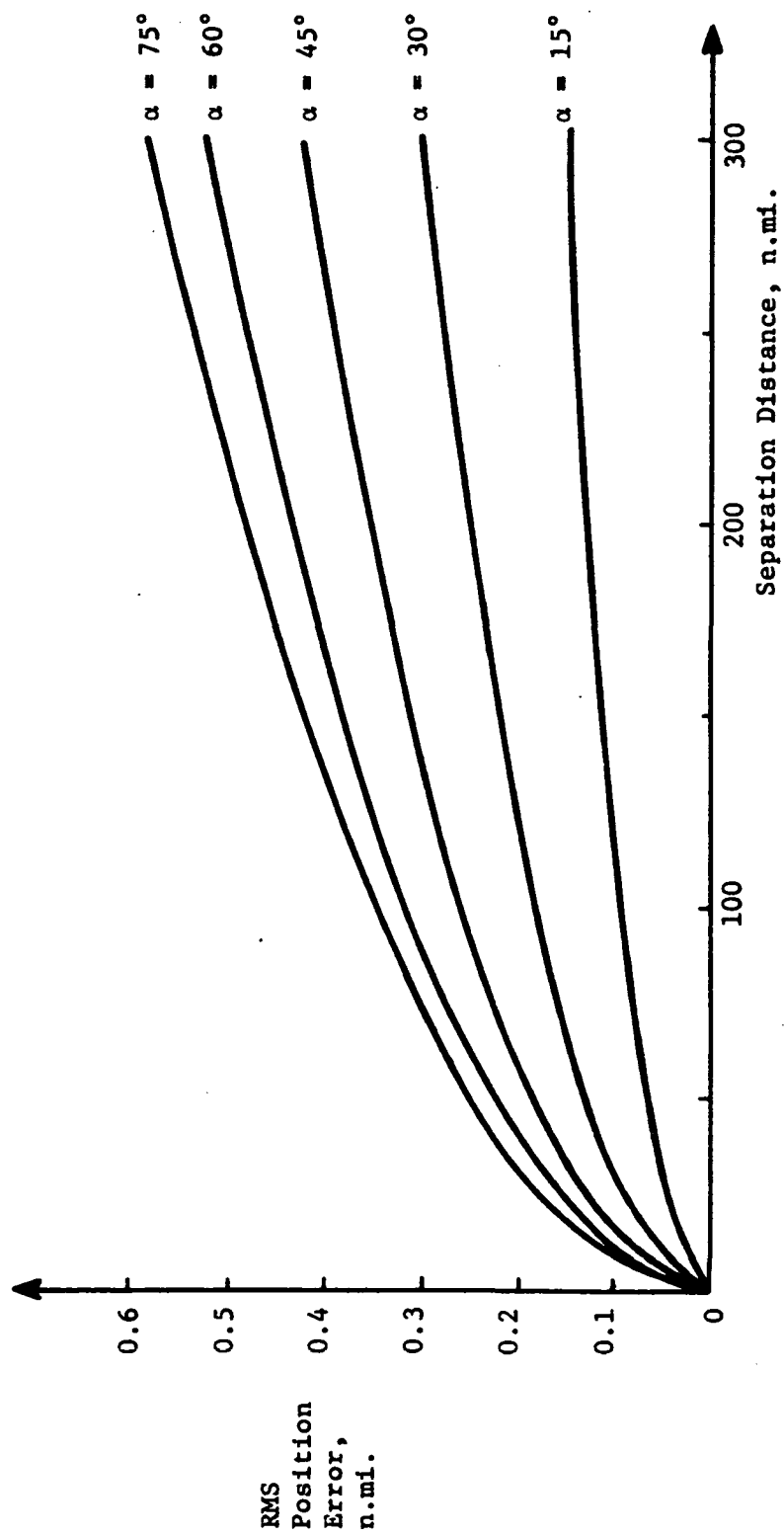


Fig. A-3. RMS differential OMEGA decorrelation error considering orientation (α) of receiver baseline to LOP.

APPENDIX B

OMEGA FIELDS NEAR THE GROUND

At large distances from a source the best treatment of VLF propagation is by waveguide theory. The relative constancy of the earth-ionosphere system allows for formulation of the problem in terms of waveguide modes; and, as in the case of most waveguides, there is one mode which is dominant. So at great distances from the transmitter, propagation can be described in terms of a single propagation factor, namely the one for the first transverse magnetic mode. The parameters of the earth-ionosphere guide change with time and distance but never enough to change the principal mode of propagation.

Near a transmitter the fields are much more complex and although they could be expanded in terms of the infinity of allowable modes in the earth-ionosphere guide there are easier ways to calculate the fields. But among these ways there is not just one dominant field solution and so at any one point a sum of solutions must be taken. These near-fields are not considered here because OMEGA navigation should never be dependent on a close transmitter. In the vicinity of a transmitter (conventionally within 600 n.mi. (1111.20 km)) fields are present that are called skywaves, ground waves, trapped surface waves, and space waves and these are not waveguide type solutions.

B.1 Mode Generation

Following J. R. Wait (ref. 35), the relevant mode theory for OMEGA can be understood by considering the case of a parallel plate perfect conductor with a dipole source as shown in Figure B-1.

The dipole and its images all radiate in phase so the fields due to all of them will add when the phase front is an integer number of wavelengths from each one. The zeroth order mode would be described by the phase front being the same number of wavelengths from each source, in which case the propagation direction would be parallel to the plates. This mode is actually transverse electromagnetic and is allowed in the earth-ionosphere guide, but is attenuated

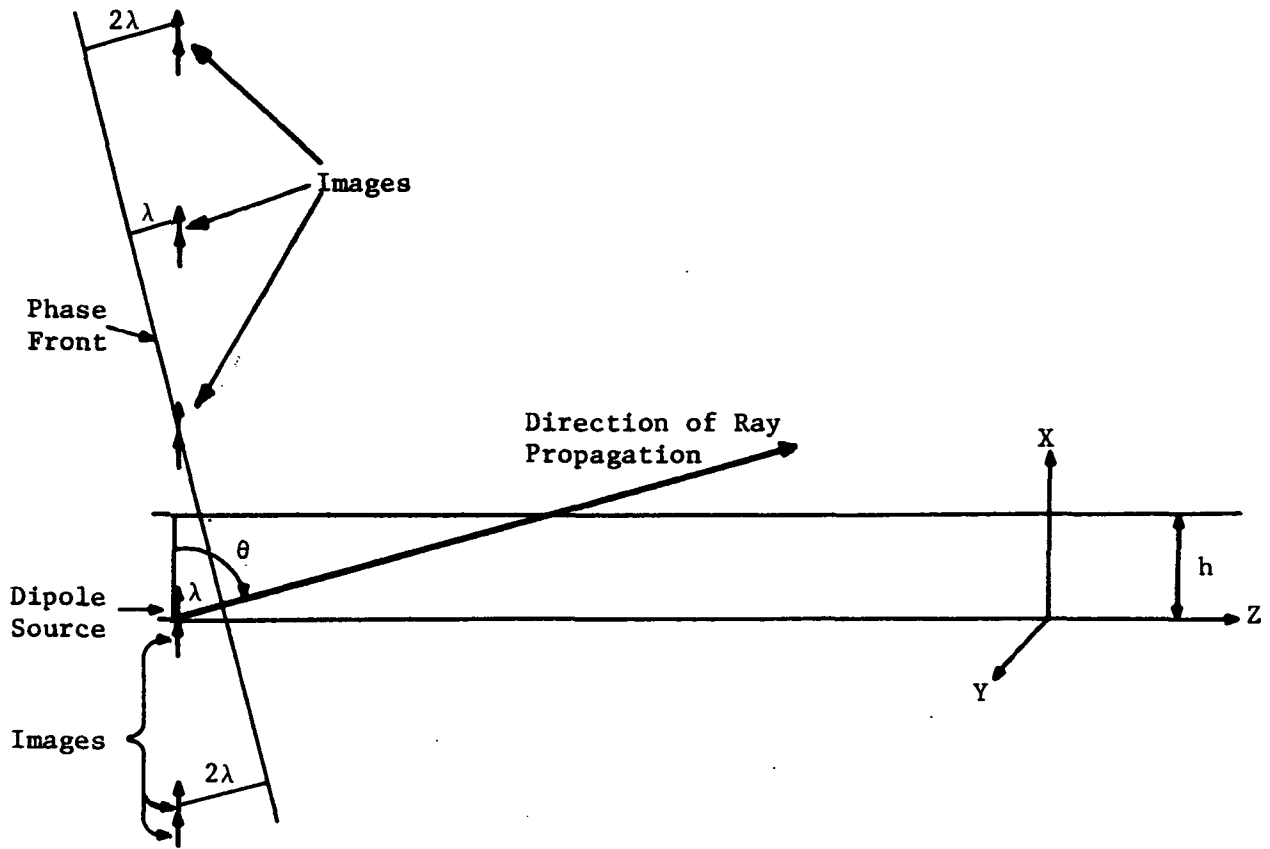


Fig. B-1. Ray geometry of dipole images showing first order mode between parallel plates.

by lossy waveguide walls, even though it would be the primary mode in the perfectly conducting case. The rest of modes are resonant when $2h\cos\theta = n\lambda$, as can be seen from Figure B-1. The more general form of the resonance condition that is applicable for the imperfectly conducting earth-ionosphere guide is

$$R_g(\cos\theta) R_i(\cos\theta) \exp \{-i2hk\cos\theta\} = \exp \{-i2\pi n\} = 1$$

which reduces to $2h\cos\theta = n\lambda$ when $R_g = R_i = 1$.

$R_i(\cos\theta)$ and $R_g(\cos\theta)$ are the angle dependent plane wave reflection coefficients for the ionosphere and ground respectively, k is the free space propagation constant, and h is the ionospheric reflection height.

B.2 Perfectly Conducting Case

The fields in the guide far from the source can be thought of as the sum of two plane waves, one traveling up at angle θ with the perpendicular, and one down at $180^\circ - \theta$. In the case of perfectly conducting walls this will result in a field distribution of

$$E_z = A \sin \frac{\pi x}{a} \cos \beta z$$

$$E_x = -\beta \frac{a}{\pi} A \cos \frac{\pi x}{a} \sin \beta z$$

$$H_y = -\frac{\omega \epsilon_0 a}{\pi} \cos \frac{\pi x}{a} \sin \beta z$$

where

$$\beta = \sqrt{\left(\frac{n\pi}{a}\right)^2 - \left(\frac{2\pi}{\lambda}\right)^2}, \quad n = 1 \text{ for TM}_{10}$$

$$a = 60 \text{ to } 90 \times 10^3 \text{ meters}$$

$$\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$$

Close to the ground x is small with respect to the height of the guide

$$\sin \frac{\pi x}{a} \approx 0 \text{ and } \cos \frac{\pi x}{a} \approx 1$$

and so the fields may be approximated by

$$E_z = 0$$

$$E_x = -\beta \frac{a}{\pi} A \sin \beta z$$

$$H_y = -\frac{\omega \epsilon_0 a}{\pi} A \sin \beta z$$

In the perfect conductor case, then, the fields near the bottom of the guide will be like those of a plane wave moving horizontal to the ground with propagation factor $\sin \beta z$ and with wave impedance

$$\frac{E_x}{H_y} = \frac{\beta}{\omega \epsilon_0} = \frac{\sqrt{\left(\frac{\pi}{a}\right)^2 - \left(\frac{2\pi}{\lambda}\right)^2}}{2\pi f \epsilon_0}$$

where f is the OMEGA frequency.

At night the ionosphere will be at about 90 km and at day 60 km resulting in wave impedances of

$$\eta_{\text{night}} = 371\Omega$$

$$\eta_{\text{day}} = 364\Omega$$

for the equivalent plane wave at 10.2 kHz.

B.3 Imperfectly Conducting Case

The actual earth and ionosphere are of course not perfect conductors and in the case of the ionosphere there is no clearly definable height at which reflection takes place. But these difficulties are overcome by assuming reflection occurs at the point where a particular electron density occurs, and then assuming an equivalent sharp boundary at that point.

At the ionosphere the reflection coefficient is dependent on the angle of incidence, the relative direction and magnitude of the earth's magnetic field, and the shape of the electron density profile. The angle of incidence and the electron density profile are pretty well fixed by the time of day and year, and the effect of the earth's magnetic field is fixed by the latitude and direction of propagation. At OMEGA frequencies the ionospheric reflection coefficient behaves more like a magnetic boundary than an electrical boundary which means that R_1 is better approximated by -1 rather than +1 as in the perfectly conducting case. Typical daytime reflection coefficients at 10 kHz vary from .8 for propagation from west toward east to .7 for east toward west. The phase of the coefficients will differ by 3 or 4 degrees. The results of this are a larger phase velocity and a higher attenuation rate for propagation from east to west. At night, attenuation is lower because the ionosphere is more sharply bounded and the reflection coefficient magnitudes are about 10% greater.

Both sea water and land are conductors at OMEGA frequencies. Land, however, at the high angles of incidence characteristic of the first order mode, is much more lossy than seawater. For example, at an angle of incidence of 85° , seawater, with $\sigma = 4$ and $\epsilon = 80\epsilon_0$, has a reflection coefficient very nearly equal to 1 while leached land, with $\sigma = 10^{-3}$ and $\epsilon = 10\epsilon_0$, has a reflection coefficient equal to .55 at a phase of -24.8° for OMEGA waves.

To focus attention on the shape of the fields near the ground, a first order approximation for the ionosphere will be assumed, namely a reflection coefficient equal to -1. Also flat earth approximations will be used since the fields to be discussed are far from the transmitter.

The TM_{10} mode bounded by a perfect magnetic boundary above and a perfectly conducting boundary below will have a resonance equation

$$R_g R_i e^{-2ikhc} = e^{-2i\pi n}$$

with $R_g = 1$ and $R_i = -1$ and $n = 1$

$$c = \cos\theta = \frac{\lambda}{4h}$$

for $h = 70$ km (daytime) $c = .107$, $\theta = 83.8^\circ$

for $h = 90$ km (night) $c = .083$, $\theta = 85.2^\circ$.

The equation for these fields will be, using notation consistent with Figure B-1,

$$E_z = A \sin \frac{\pi x}{2a} \cos \beta z$$

$$E_x = -\beta \frac{2a}{\pi} A \cos \frac{\pi x}{2a} \sin \beta z$$

$$H_y = -\frac{\omega \epsilon_0 2a}{\pi} A \cos \frac{\pi x}{2a} \sin \beta z$$

The impedance of the equivalent plane wave will be formally the same as in the perfectly conducting ionosphere case

$$\frac{E_x}{H_y} = \frac{\beta}{\omega \epsilon_0}$$

where

$$\beta = \sqrt{\left(n\pi - \frac{\pi}{2}\right)^2 - \omega^2 \mu \epsilon}$$

and so

$$\begin{aligned} \frac{E_x}{H_y} &= \frac{\sqrt{\left(\frac{\pi}{2a}\right)^2 - \left(\frac{2\pi}{\lambda}\right)^2}}{2\omega \epsilon_0} = 375\Omega \text{ nighttime} \\ &= 374\Omega \text{ daytime.} \end{aligned}$$

Sea water is a good conductor at VLF while land, though it is a conductor, is not a good conductor. Low conductivity land will be about 10^{-3} mhos/meter and have a permittivity of about 10 times that of free space. As a result the reflection coefficient for ground is not 1 but a complex function of the angle of incidence. The flat-earth resonance equation cannot be simplified as before and no real-angle solution can be obtained. To illustrate this, consider the ground described above. Because the conduction current is large compared to the displacement current for 10.2 kHz

$$\frac{\sigma}{\omega \epsilon} = 176.23 \gg 1 ,$$

the displacement current in the earth may be neglected. The wave impedance in the earth is therefore

$$z_g = \sqrt{\frac{\mu}{\epsilon - i\sigma/\omega}} \approx \sqrt{\frac{i\mu\omega}{\sigma}} = \frac{1+i}{\sqrt{2}} \quad 12.871 = 9.06 (1+i) .$$

The Fresnel reflection coefficient for the ground will be

$$R_g = \frac{z_0 C - z_g}{z_0 C + z_g} ,$$

where $z_o = 377\Omega$ is the free space impedance, C is the complex cosine of the angle of incidence, and z_g is the ground impedance. In a conductor the planes of constant amplitude and constant phase are nearly parallel to the surface and so the cosine which would normally accompany z_g is approximated by 1. The resonance equation is

$$R_g R_i \exp \{-2ikhc\} = \exp \{-2i\pi n\}$$

where the variables have been previously defined. Approximate R_i with -1 and set $n = 1$ for first order mode. Then

$$R_g (-1) \exp \{-2ikhc\} = R_g \exp \{-2ikhc - i\pi\} .$$

Rearrange the terms and substitute for R_g from before, and

$$\frac{z_o C - z_g}{z_o C + z_g} = \exp \{2ikhc - i\pi\} .$$

This equation can be solved by graphical means to obtain C but an approximate solution will be done here because the exact method is no simple matter since C is complex. $|z_g|$ will be about 9 and $|z_o C|$ will be approximately 37.7 so that $z_o C + z_g$ is approximated as $z_o C$ in the second term of the expansion:

$$\frac{z_o C - z_g}{z_o C + z_g} = 1 - \frac{2z_g}{z_o C + z_g} \simeq 1 - \frac{2z_g}{z_o C} \simeq \exp \left\{ - \frac{2z_g}{z_o C} \right\} .$$

This approximation is better for land that is not so dry since the conductivity will be higher and therefore z_g lower. Taking the log of both sides and rearranging, yields

$$khc = \frac{\pi}{2} + i \frac{z_g/z_o}{C} .$$

This can be solved to yield

$$(1 - c^2)^{1/2} = \delta = \left[1 - \left(\frac{\pi}{2kh} \right)^2 \right]^{1/2} - i \frac{1}{kh} \frac{z_g}{z_o} \left[1 - \left(\frac{\pi}{2kh} \right)^2 \right]^{-1/2} .$$

For daytime 70 km ionospheric height

$$C = .0924 + i .0177$$

and the reflection coefficient is

$$R_g = .5572 \angle -24.8^\circ .$$

For nighttime 90 km ionospheric height we get

$$C = .0689 + i .0184$$

and

$$R_g = .4449 \angle -31.4^\circ .$$

B.4 Fields Near the Ground

The fields near the ground in the imperfectly conducting case may now be calculated. The field in the direction of travel, E_z , will no longer be zero as in the perfectly conducting case. Postulate the form of z component as

$$E_z = A \cos \beta z .$$

Then H_y , which is composed of an incident and reflected wave, will be

$$H_y = H_{yI} + H_{yR} = H_{yI} + R H_{yI} .$$

But,

$$\frac{E_z}{H_y} = z_g , \quad H_y = \frac{E_z}{z_g}$$

and

$$E_x = E_I \sin \theta + E_R \sin \theta$$

$$= \eta H_I \sin \theta + \eta H_R$$

$$= \eta H_I \sin \theta (1 + R)$$

$$= \eta \sin \theta H_y .$$

In the case of $\sigma = 10^{-3}$ h = 70 km (daytime),

$$E_z = A \cos \beta z$$

$$H_y = \frac{A}{z_g} \cos \beta z = .078 \angle -45^\circ A \cos \beta z$$

$$E_x = 377 (.9959 + i.0177) \frac{A}{9.06} \frac{1}{(1 + i)} \cos \beta z$$

$$= 29.3 \angle -45.1^\circ A \cos \beta z .$$

And for $\sigma = 10^{-3}$ h = 90 km (night)

$$E_z = A \cos \beta z$$

$$H_y = \frac{A}{z_g} \cos \beta z = .078 \angle -45^\circ A \cos \beta z$$

$$E_x = 377 \frac{(.9978 - i0.0013)}{9.06(1 + i)} A \cos \beta z$$

$$= 29.36 \angle -45.1^\circ .$$

APPENDIX C

GEODETIC RANGE AND AZIMUTHAL CALCULATIONS

In calculating range and azimuth between receiver sites and between each receiver site and transmitter stations a computer algorithm has been obtained from the Hydrographic Center of the Defense Mapping Agency which is now responsible for generating the published skywave corrections for OMEGA.

The computer algorithm is a method devised by E. M. Sodano and is described in the GIMRADA research note No. 11, April 1963, and is termed the Fifth Inverse Method of Sodano. The distance between any two points described in terms of latitude and longitude is calculated along the geodesic between the two points. The azimuth of this geodesic at the first point measured clockwise from geodetic south (180° from geodetic north) is also provided.

Input parameters include equational earth radius (EQRAD), polar earth radius (PORAD), latitude and longitude of first point in radians (RLAT1, RLON1) and latitude and longitude of the second point in radians (RLAT2, RLON2). The variables DIST and AZ output the geodetic distance in the same units as the spheroid constants (EQRAD and PORAD) and azimuth in radians respectively.

The earth radius values used in OMEGA related calculations are*

$$\text{EQRAD} = 6378166 \text{ m}$$

$$\text{PORAD} = 6356784.283 \text{ m.}$$

A FORTRAN listing of this subroutine is provided in Fig. J-1, Appendix J. The argument CFLG is a flag which must be zero upon initial entry and should be set to zero thereafter each time the spheroid constants are changed.

*These are the Fischer earth parameters based on EQRAD and a flattening parameter $\left[\frac{\text{EQRAD} - \text{PORAD}}{\text{EQRAD}} \right] = \frac{1}{298.3}$.

APPENDIX D

ANALYSIS OF NASA OMEGA DIGITAL PHASE-LOCKED LOOP

The NASA-built OMEGA receiver employs a digital phase-locked loop for each of stations A, B, C, and D for each OMEGA frequency (total of 12 loops). Originally the loops were implemented as second order loops shown in Figure D-1.

The discriminator characteristic is illustrated in Figure D-2. Considering only the range of phase differences from lock on the interval ± 25 cec the effective discriminator output is linearly related to the average phase difference from lock so that a difference of ± 25 cec results in an output count of ± 16.32 counts or 4.08 cec (4 of the 4.08 MHz counts equals 1 cec of phase at 10.2 kHz) correction output to the feedback channel. Thus the gain of the phase detector is $16.32/25 = 0.6528$ per 10 seconds or correction output is 0.6528 times the phase difference for phase differences in the range ± 25 cec. Analyzing the discriminator characteristic further it can be seen that the correction count v_d is related to the phase difference by

$$v_d = K_d (\phi_R - \phi_L) + \alpha \quad (D-1)$$

where K_d is the detector gain ($= 0.6528$), ϕ_R is the received signal phase, ϕ_L is the effective loop phase (both in cec) and α is a constant determined from the discriminator characteristic. Over the range ± 50 cec the values of α and K_d are as follows:

$$- 25 \leq (\phi_R - \phi_L) \leq 25 : K_d = 0.6528; \alpha = 0$$

$$25 \leq (\phi_R - \phi_L) < 50 : K_d = - 0.6528; \alpha = 32.64$$

$$- 50 < (\phi_R - \phi_L) \leq - 25 : K_d = - 0.6528; \alpha = - 32.64$$

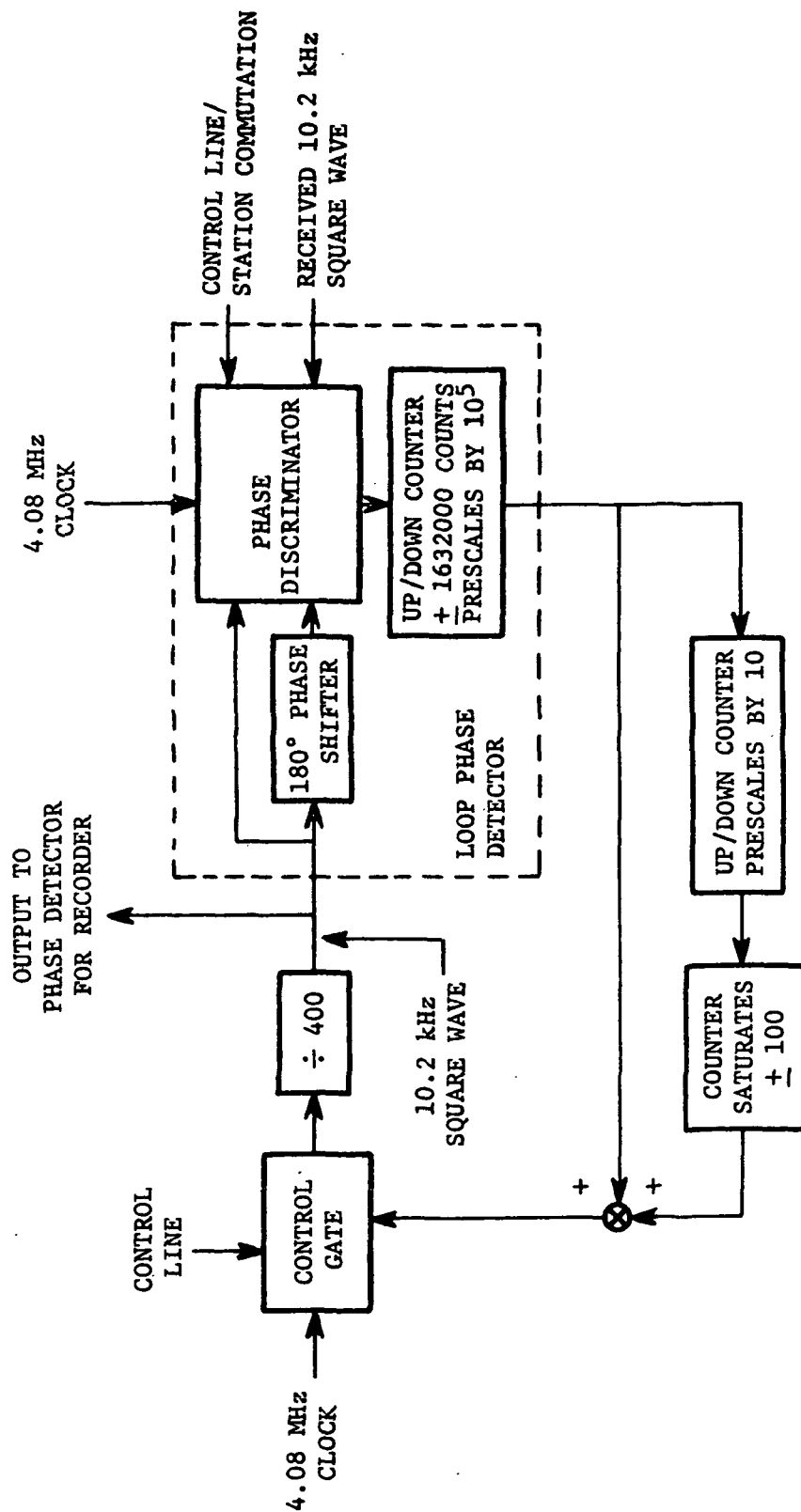
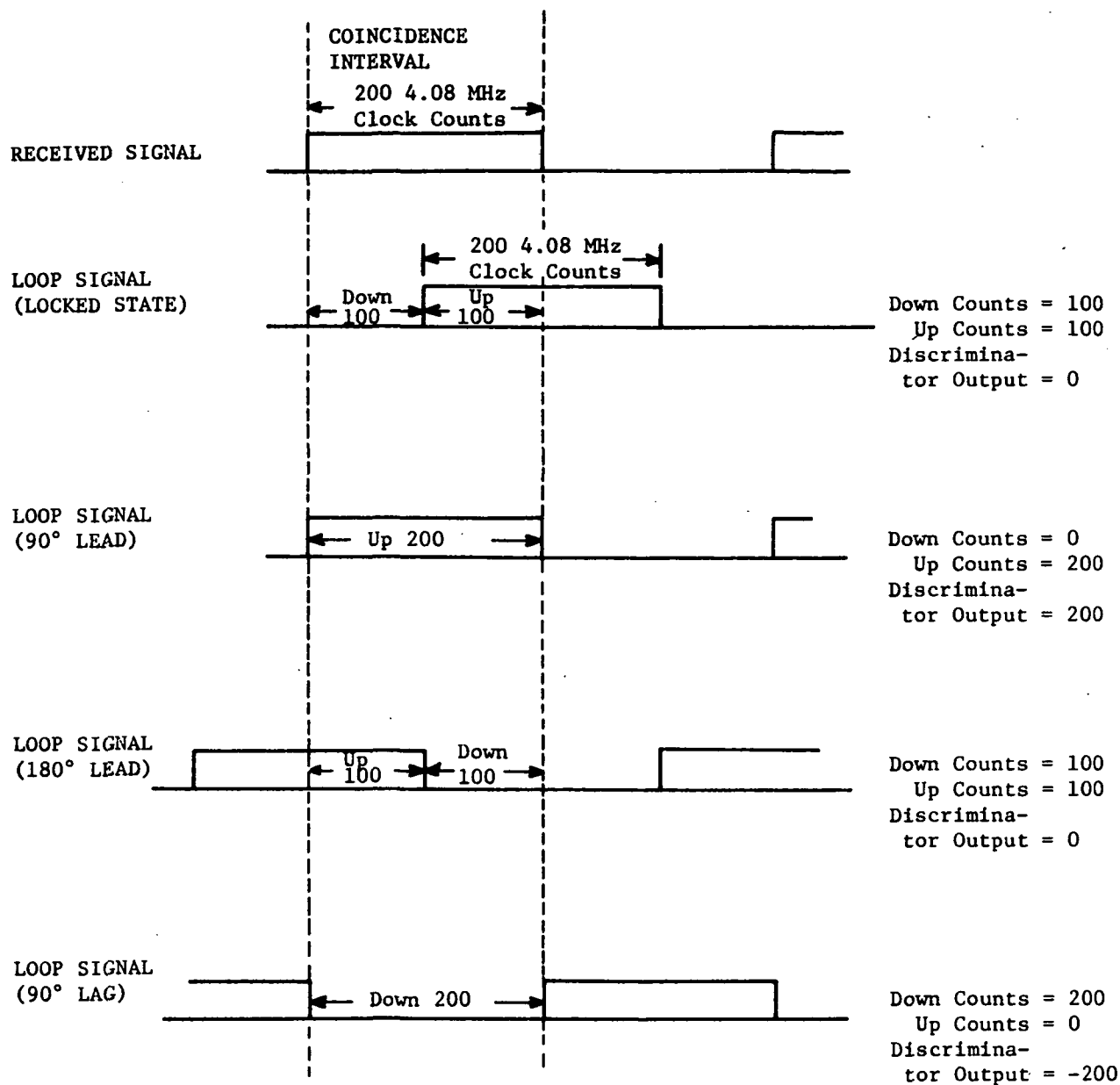
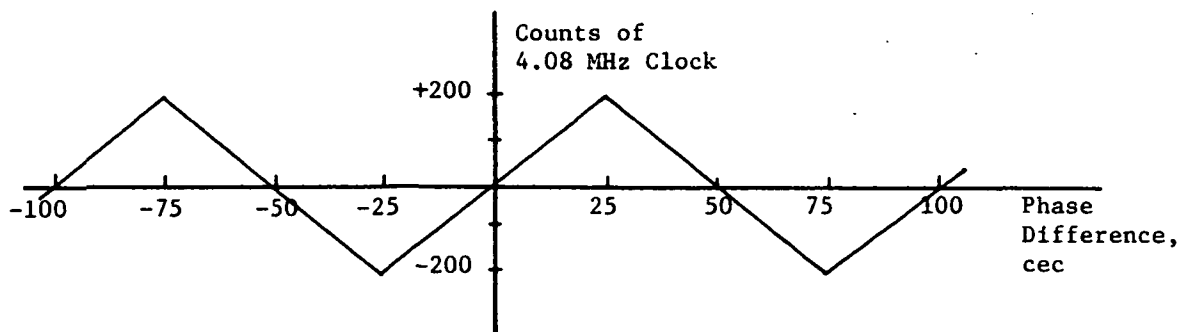


Fig. D-1. NASA Langley digital phase-locked loop (second order) for OMEGA receiver.



(a) One Cycle Examples of Relative Loop Phase



(b) Discriminator Characteristic

Fig. D-2. Characteristics of loop phase discriminator.

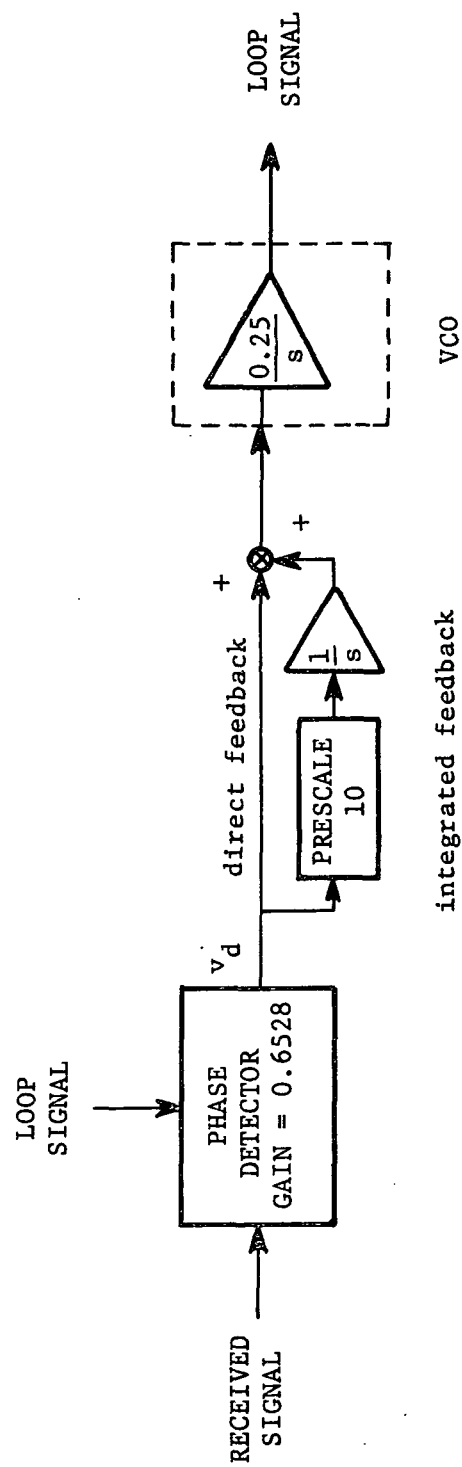


Fig. D-3. Feedback channels for phase-locked loop receiver constants are 10 sec values.

It should be noted that if the phase difference from lock is exactly + 50 cec or - 50 cec no discriminator output will be present. Otherwise the loop discriminator output will tend to drive the loop phase toward the stable zero point. Also note that ϕ_L represents the effective loop phase which is 25 cec displaced from the actual loop phase since the loop is locked when the loop phase is 25 cec out of phase with the received signal. Thus $(\phi_R - \phi_L)$ represents a phase difference from lock in cec.

The discriminator prescaler acts as an accumulator since the feedback channel will only be affected in any one 10 second period by an integer number of counts. This "accumulator" in the prescaler saves any fractional counts and adds these to the discriminator output at the next measurement interval.

The discriminator output in whole counts is input to a two channel feedback line in the second order loop. Since the output of the feedback line is such that one count of feedback changes the phase of the loop signal by 1/4 cec (one count) then the control gate/divider is effectively a voltage controlled oscillator (VCO) with a gain of 1/4 cec per count.

The phase-locked loop diagrammed in Figure D-1 can be represented in terms of the feedback line using more conventional phase-locked loop component terms as in Figure D-3. Note that if the term "counts" is replaced by the word "voltage" then v_d in (D-1) conforms to a conventional analog discriminator equation in which a feedback voltage is used to drive a VCO.

For an analog or "perfect" second order phase-locked loop the diagram would look much like that of Figure D-3 except the prescaler in the integrated feedback channel would be replaced by an amplifier with a gain of 0.1. The operation of the digital prescaler-counter matches the operation of an analog amplifier-integrator except that counters integrate in discrete steps. The operation of the prescaler in the digital phase detector, however, is not associated directly with an integrator in this second order loop so that the overall feedback channel does not match the perfect analog second order channel exactly. To illustrate this analytically consider the digital phase-locked loop with x_i the 10 second average phase difference between the loop phase and the received phase at the i th measurement interval measured in counts. The accumulated feedback output at time k from the direct channel is

$$Z_k = \text{IFIX} \left\{ \sum_{i=1}^k \frac{x_i}{10^5} \right\}$$

where $\text{IFIX} \{ \cdot \}$ represents "integer portion of" which is the prescaler output in the digital operation. The corresponding accumulated VCO input considering all feedback up to time k is then

$$Z_k + \text{IFIX} \left\{ \sum_{i=1}^k \frac{Z_i}{10} \right\} = Z_k + \text{IFIX} \left\{ \sum_{i=1}^k \left[\frac{1}{10} \text{IFIX} \left(\sum_{j=1}^i \frac{x_j}{10^5} \right) \right] \right\}$$

where Z_k is the portion contributed by the direct channel output and $\text{IFIX} \left\{ \sum_{i=1}^k \frac{Z_i}{10} \right\}$ is the accumulated integrator channel output. The VCO output at time k is shifted in phase by the accumulated feedback and this shift can be expressed as

$$y_k = \text{IFIX} \left\{ \sum_{i=1}^k \frac{x_i}{10^5} \right\} + \text{IFIX} \left\{ \sum_{i=1}^k \frac{1}{10} \text{IFIX} \left[\sum_{j=1}^i \frac{x_j}{10^6} \right] \right\} \quad (\text{D-2})$$

where y_k is in counts.

The perfect second order analog phase-locked loop would have a VCO output at time T of

$$y(T) = \frac{1}{10^5} \int_0^T \left\{ x(t) + \int_0^t \frac{1}{10} x(\tau) d\tau \right\} dt$$

and can be represented digitally at time k as

$$y'_k = \text{IFIX} \left\{ \sum_{i=1}^k \frac{x_i}{10^5} \right\} + \text{IFIX} \left\{ \sum_{i=1}^k \sum_{j=1}^i \frac{x_j}{10^6} \right\} . \quad (\text{D-3})$$

Comparing the two loop feedback equations (D-2) and (D-3), it can be seen that they are equivalent iff

$$\sum_{j=1}^i \frac{x_j}{10^6} = \frac{1}{10} \text{IFIX} \left[\sum_{j=1}^i \frac{x_j}{10^5} \right] . \quad (\text{D-4})$$

By inspection (D-4) does not hold except when the sequence $\left(\frac{x_j}{10^5} \right)$, $j = 1, 2, \dots, i$, is a sequence of integers which is not, in general, the case. In fact from (D-4)

$$\sum_{j=1}^i \frac{x_j}{10^6} \geq \frac{1}{10} \text{IFIX} \left\{ \sum_{j=1}^i \frac{x_j}{10^5} \right\}$$

for each j such that the feedback given by (D-3), y'_k , is greater than or equal to the feedback given by (D-2), y_k . For the gain constants used the quantities $\frac{x_j}{10^5}$ have zero probability of always being integers so that in general

$$y'_k > y_k \quad k > 1$$

for any given noiseless signal.

This means that the second order digital phase-locked loop as described and represented in Figures D-1 and D-3 actually has reduced gain in the feedback channel from that associated with the perfect second-order loop. This causes the response of the loop to a phase ramp input to be slightly underdamped. That this is the case has been shown using receiver simulation results run on the RTI PDP-8/e digital computer. Figure D-4 provides

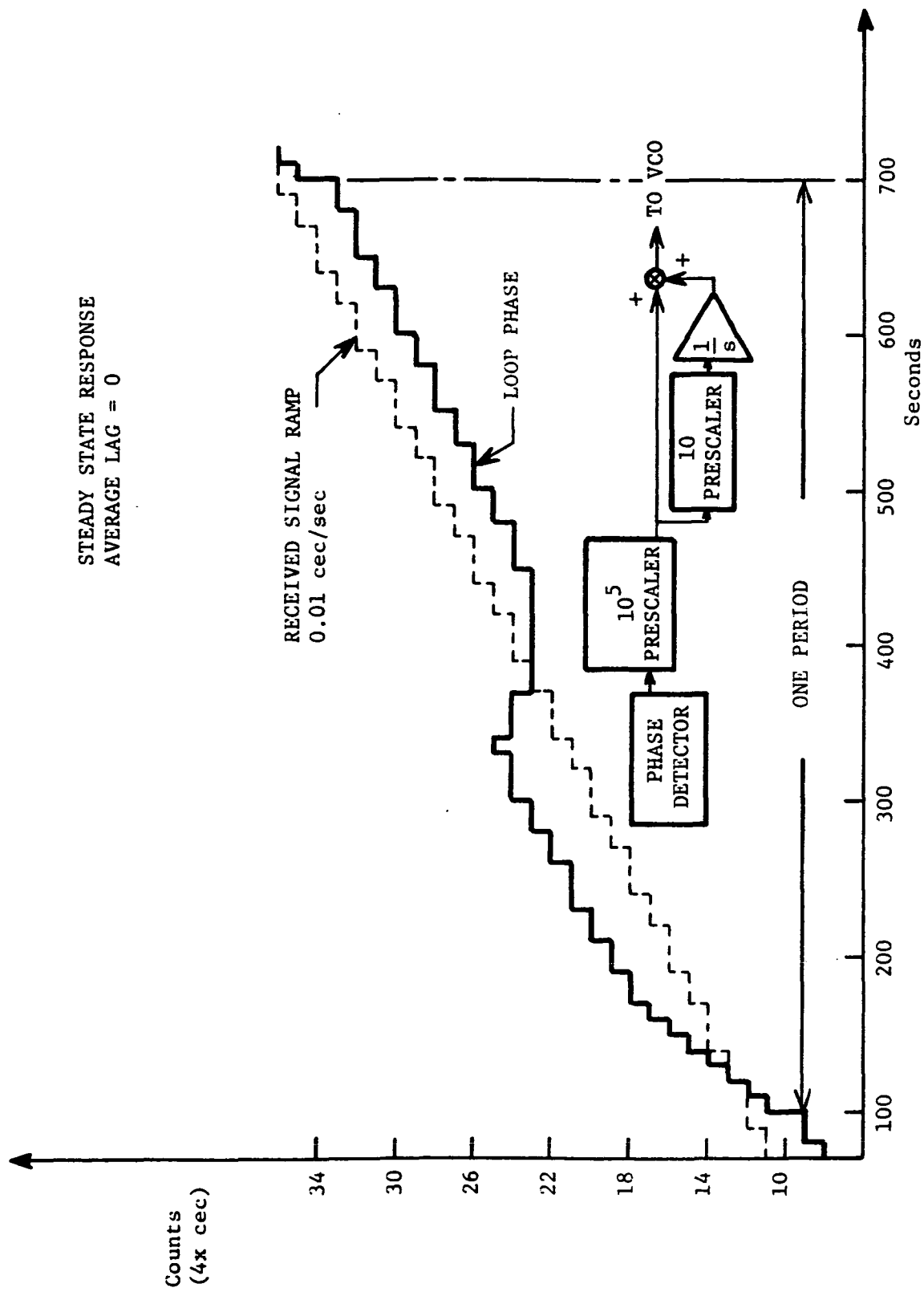


Fig. D-4. NASA Langley second order digital phase-locked loop tracking a ramp input.

response of the digital loop described in Figures D-1 and D-3. A phase ramp input of 0.01 cec/sec (10^{-4} Hz) was provided as input and output plotted over one period of the oscillatory tracking response in the steady state situation. The average phase lag is zero but the instantaneous error is as large as 1 cec. This can lead to low frequency distortion in tracking a received phase with the oscillatory period of the response dependent on the slope of the ramp, and this oscillation would be very difficult to remove from the data.

An implementation of (D-3) is given in Figure D-5. The phase detector simply accumulates counts during a measurement interval, its output is dumped into the feedback channel and it is cleared before the next measurement period. Only one prescaler is used at the output of the feedback channel. The response of this when implemented on the digital computer is given in Figure D-6. A ramp input of .01 cec per sec (10^{-4} Hz) is used and the output is shown for 600 seconds of 10 second measurement intervals. The track is almost perfect. There is some evidence of an underdamped response which should be the case since the VCO phase can only be shifted in discrete steps; however, the response is considerably better than that shown in Figure D-4.

The first order loop derived from the receiver represented in Figures D-1 and D-3 was also investigated. This is implemented by simply disconnecting the integrated feedback channel. Figure D-7 provides the response of this first order loop to a simulated ramp input of .01 cec/sec (10^{-4} Hz). As is true of the first order analog loop the receiver will not track a phase ramp perfectly. The loop ramp has the same slope as the input ramp but there is a constant offset or lag in the phase response. For the ramp input used, the phase lag was measured to be 0.612745 cec in the steady state. This corresponds to a time lag of 61.27 seconds of loop operation which is slightly more than six 10 second measurement intervals. This lag is a function of the slope of the ramp input. Table D-1 presents results for six different ramp inputs from .0075 cec/sec (75×10^{-6} Hz) to 0.025 cec/sec (2.5×10^{-4} Hz) showing a tracking error of from 0.4596 cec to 1.5318 cec. The tracking error $\Delta\epsilon_{ss}$ is related to the ramp phase rate, $\Delta\omega$ by

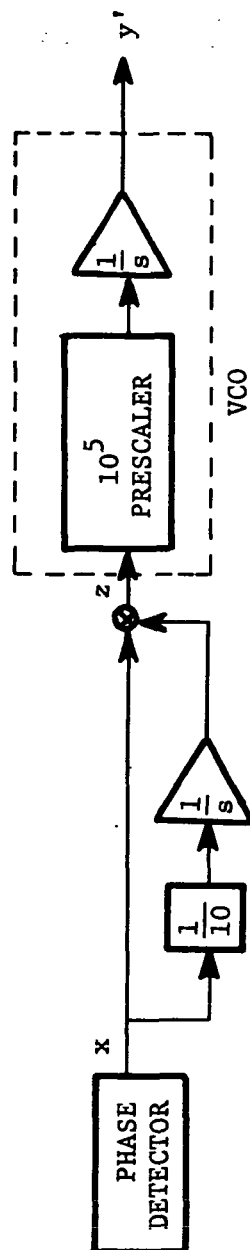


Fig. D-5. Feedback channel of digital model of perfect second order PLL.

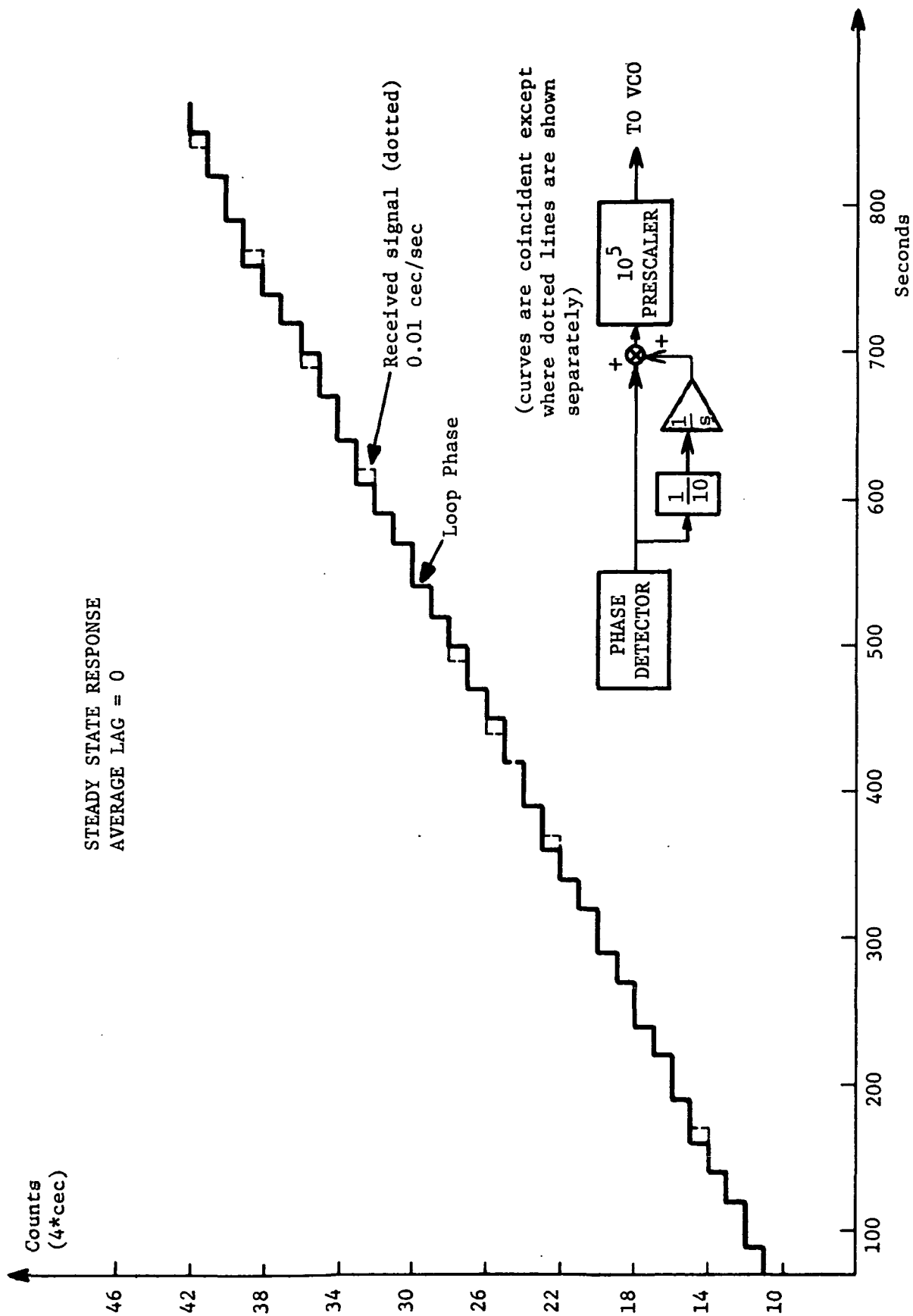


Fig. D-6. Digitally implemented "perfect" second phase-locked loop tracking a ramp input.

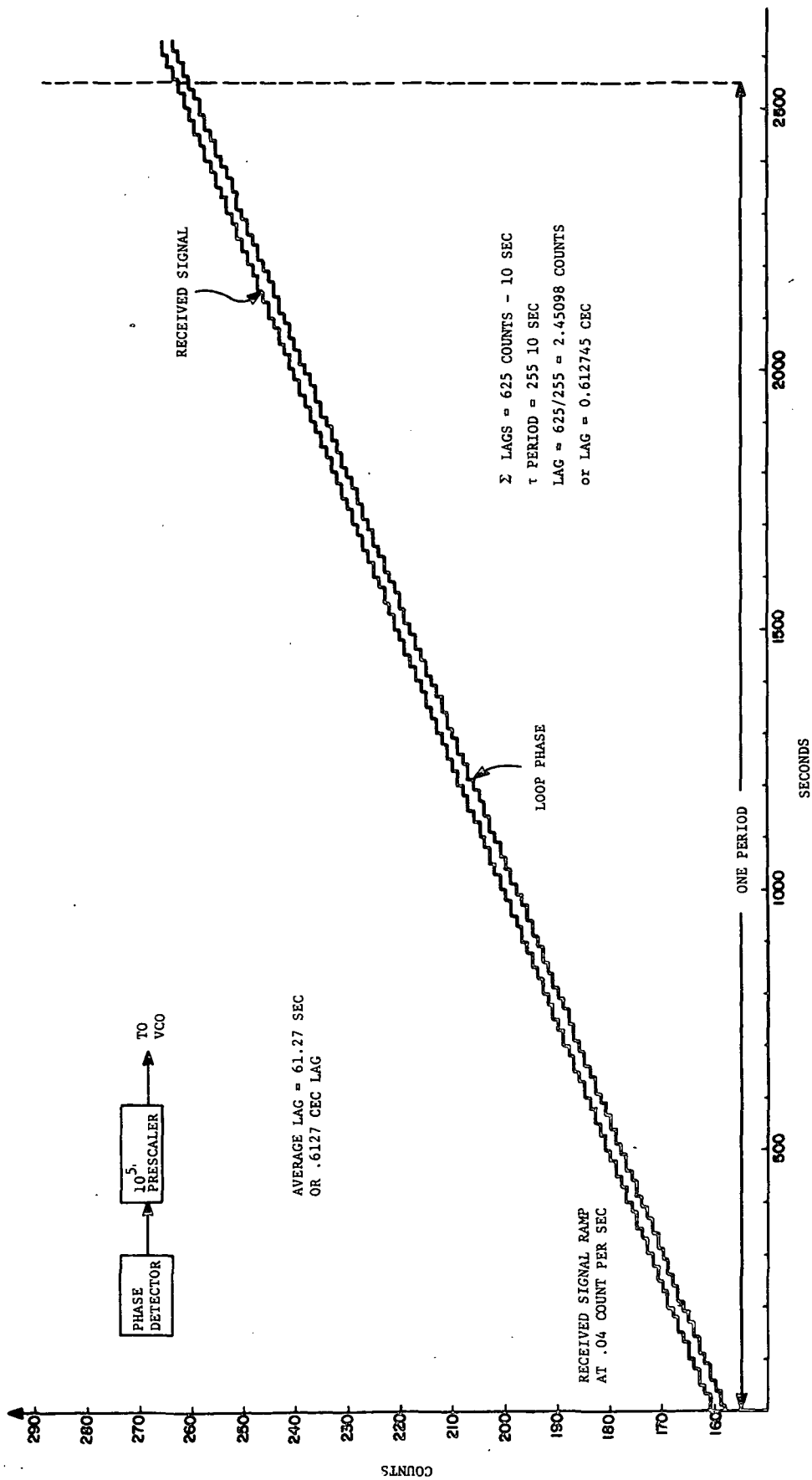


Fig. D-7. LRC first order digital phase-locked loop tracking a phase ramp (steady state).

$$\Delta\epsilon_{ss} = 61.27 \Delta\omega \quad (D-5)$$

where $\Delta\omega$ is in cec/sec and $\Delta\epsilon_{ss}$ is in cec.

Table D-1. Tracking Error of First Order Digital Loop with Phase Ramp Input

Ramp Input $\Delta\omega$ in cec/sec	Loop Tracking Error $\Delta\epsilon_{ss}$ (cec)
0.0075	0.4596
0.010	0.6127
0.0125	0.7659
0.015	0.9191
0.020	1.2255
.025	1.5318

The simulation results that have been presented have assumed a noiseless situation. The phase detectors are considered perfect and there is no error in presenting the "received" signal to the detector. All digital operations have been considered to be perfect.

D.1 The Analog Phase-Locked Loop

Consider an analysis of the first-order and second-order analog phase-locked loops (PLL) which use the same gain constants as the NASA built digital loops. Analysis is restricted to phase tracking errors of 25 cec or less because of the discontinuity in the digital phase discriminator characteristic.

Figure D-8 illustrates the analog PLL using the 10 second constant values. To change this to a real time model each s is replaced by 10s so

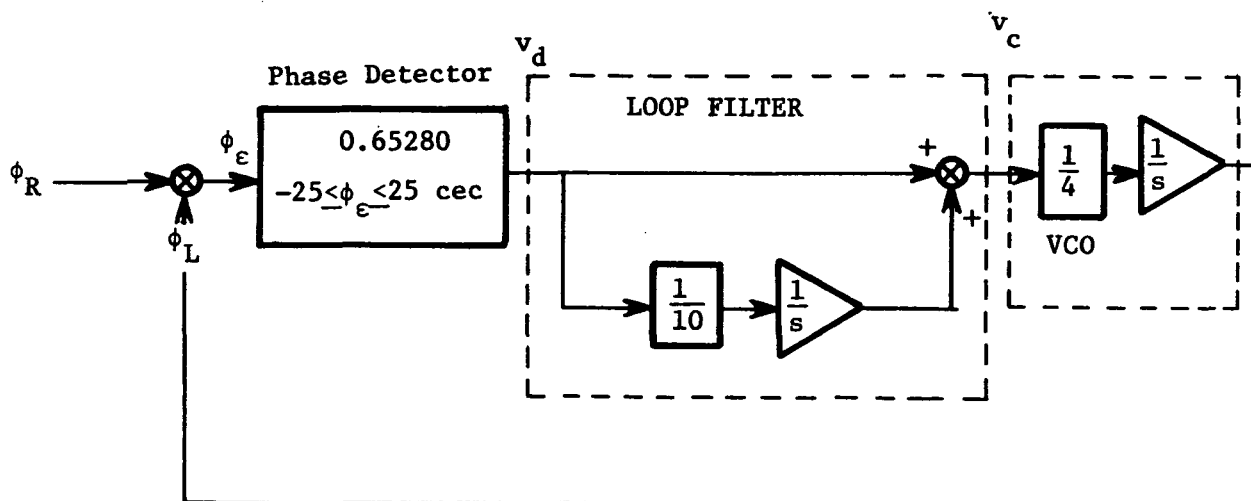


Fig. D-8. Analog model of digital phase-locked loop (PLL) receiver.
Note that all constants are 10 sec values.

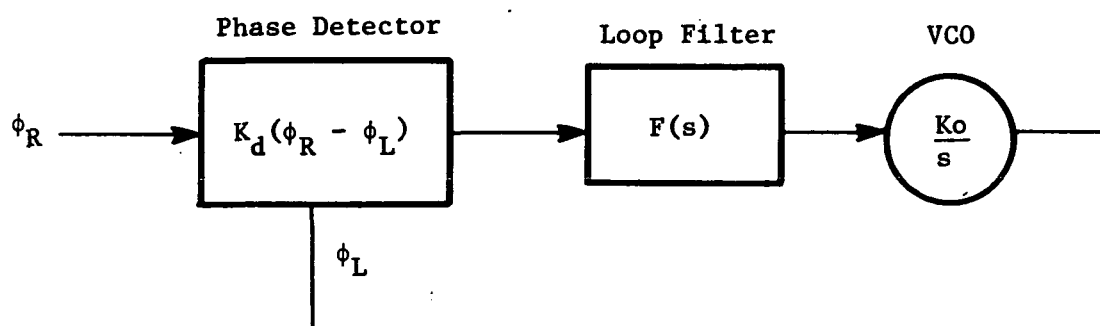


Fig. D-9. Classical PLL model.

that the classical PLL model of Figure D-9 is valid where $K_d = .6528$ and $K_o = 0.025$, and the loop filter function is

$$F(s) = 1 + \frac{1}{100s} = \frac{100s + 1}{100s} \quad (D-6)$$

In Figure D-9 ϕ_L represents the loop phase and ϕ_R represents the input phase (received phase) so that in the s domain the basic loop equations are

$$\frac{\phi_L(s)}{\phi_R(s)} = H(s) = \frac{K_o K_d F(s)}{s + K_o K_d F(s)} \quad (D-7)$$

and

$$\frac{\phi_\epsilon(s)}{\phi_R(s)} = \frac{s}{s + K_o K_d F(s)} \quad (D-8)$$

where ϕ_ϵ is the error phase, i.e., $\phi_\epsilon = \phi_R - \phi_L$. The loop transfer function of (D-7) written using (D-6) is

$$H(s) = \frac{K_o K_d s + \frac{K_o K_d}{\tau_1}}{s^2 + K_o K_d s + \frac{K_o K_d}{\tau_1}} \quad (D-9)$$

where τ_1 in (D-9) is the value of 100 in (D-6) which is the inverse of the effective integrator channel gain.

In terms of the natural frequency, ω_n , and damping factor, δ , the loop transfer function can be expressed as

$$H(s) = \frac{2\delta\omega_n s + \omega_n^2}{s^2 + 2\delta\omega_n s + \omega_n^2}$$

where

$$\omega_n = \left(\frac{K_o K_d}{\tau_1} \right)^{1/2} \quad \text{and} \quad \delta = \frac{\tau_1}{2} \left(\frac{K_o K_d}{\tau_1} \right)^{1/2} = \frac{1}{2} (\tau_1 K_o K_d)^{1/2}$$

with $K_o K_d = .01632 \text{ sec}^{-1}$ and $\tau_1 = 100 \text{ sec}$. This yields

$$\omega_n = .0128 \text{ rad/sec}$$

and

$$\delta = .639 .$$

For the second order loop the loop noise equivalent bandwidth is

$$B_L = \frac{\omega_n}{2} \left(\delta + \frac{1}{4\delta} \right) \text{ Hz} .$$

It can be noted that loop gain and noise bandwidth can be specified independently since τ is a free parameter.

This receiver can be operated as a first order loop by disconnecting the integrator channel in the feedback loop. Based on the analysis presented in the previous section, it is of interest to examine the resulting first order PLL receiver. For the first order loop the loop filter function

$$F(s) = 1$$

so that the loop transfer function is simply

$$H(s) = \frac{K_o K_d}{s + K_o K_d} .$$

In the first order loop there is a trade-off between loop gain ($K_o K_d$) and loop bandwidth (B_L) such that increasing the gain will cause the bandwidth to become large. This means that narrow bandwidth and good tracking are incompatible in the first order loop.

For the first order loop

$$\omega_n = K_o K_d \text{ and } B_L = \frac{\omega_n}{4} \text{ Hz}$$

where B_L is the noise equivalent bandwidth. The time constant of this first order loop is $\frac{1}{K_o K_d} = 61.27$ seconds.

The receiver of Figure D-9 operated as either a first or second order loop has parameter characteristics as defined in Table D-2 (see ref. 29). As can be seen from this table the steady-state phase error of the first order loop is $\Delta\omega/K_o K_d$ where $\Delta\omega$ is the frequency shift of the received frequency, i.e., a ramp input. This yields an error of $61.27\Delta\omega$ cec when tracking a ramp which is the same relationship that was determined using the digital simulation model and given in (D-5). This relationship is plotted in Figure D-10 and the points identified in Table D-1 fall on this line.

D.2 Received Signal With Noise

Noise in the received signal can be described as phase jitter at the input to the phase detector. This is inversely proportional to the signal-to-noise ratio at the input of the detector.

Let $\bar{\theta}_{ni}^2$ be the variance of the input phase jitter noise, P_n be the total noise power in the input, P_s the input signal power so that the signal to noise ratio at the detector input is

$$(\text{SNR})_i = 10 \log \frac{P_s}{P_n} = 10 \log \frac{1}{2\bar{\theta}_{ni}^2} .$$

For

$$[\bar{\theta}_{ni}^2]^{1/2} = 2.5 \text{ cec, then}$$

$$(\text{SNR})_i = 13.067 \text{ dB.}$$

Figure D-11 is the simulated response of the first and second order digital PLL receiver based on the implementation of Figures D-1 and D-3 and the modified second order PLL receiver of Figure D-5 with an input signal-to-noise ratio of 13.067 dB. An initial offset phase is followed by a ramp input of 75×10^{-4} cec/sec (27cec/hour). Since the loop noise bandwidth

Table D-2. Analog PLL Characteristics

LOOP TYPE	ω_n	δ	Gain ($K K_d$)	$H(s)$	Noise- Equivalent Bandwidth B_L	Steady-State Ramp Tracking Error
FIRST ORDER	.01632 rad/sec .0026 Hz	-	.01632	$\frac{K K_d}{s + K K_d}$	$\frac{K K_d}{4} = .00408 \text{ Hz}$	$\frac{\Delta\omega}{K K_d} = \frac{\Delta\omega}{.01632} \text{ cec}$
SECOND ORDER	.0128 rad/sec .00203 Hz	.639	.01632	$\frac{K K_d (s + 1/\tau_1)}{s^2 + K K_d s + \frac{K K_d}{\tau_1}}$	$\frac{K K_d + 1/\tau_1}{4} = .00658 \text{ Hz}$	0

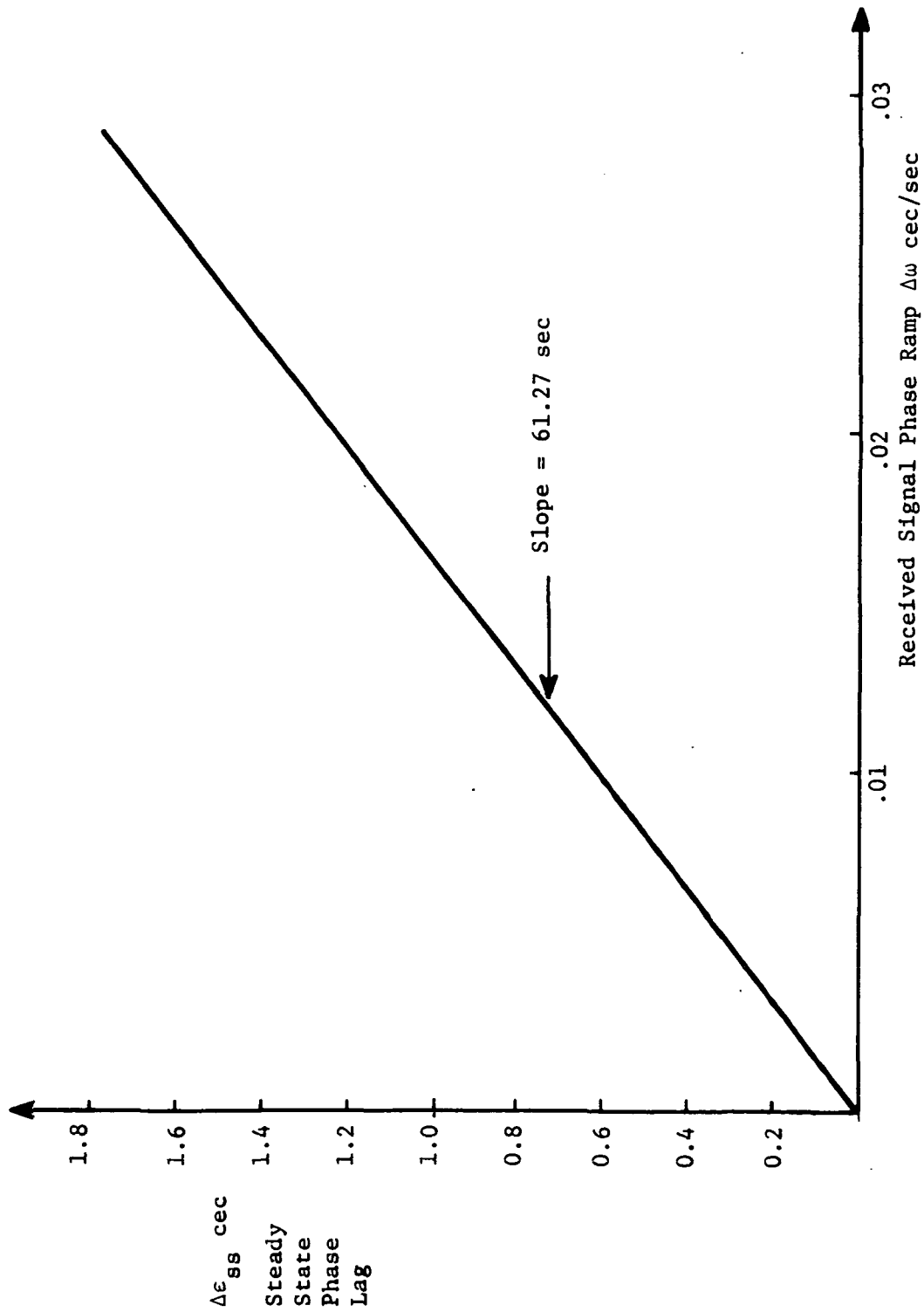


Fig. D-10. Loop phase lag error as a function of received signal phase ramp, first order digital phase-locked loop.

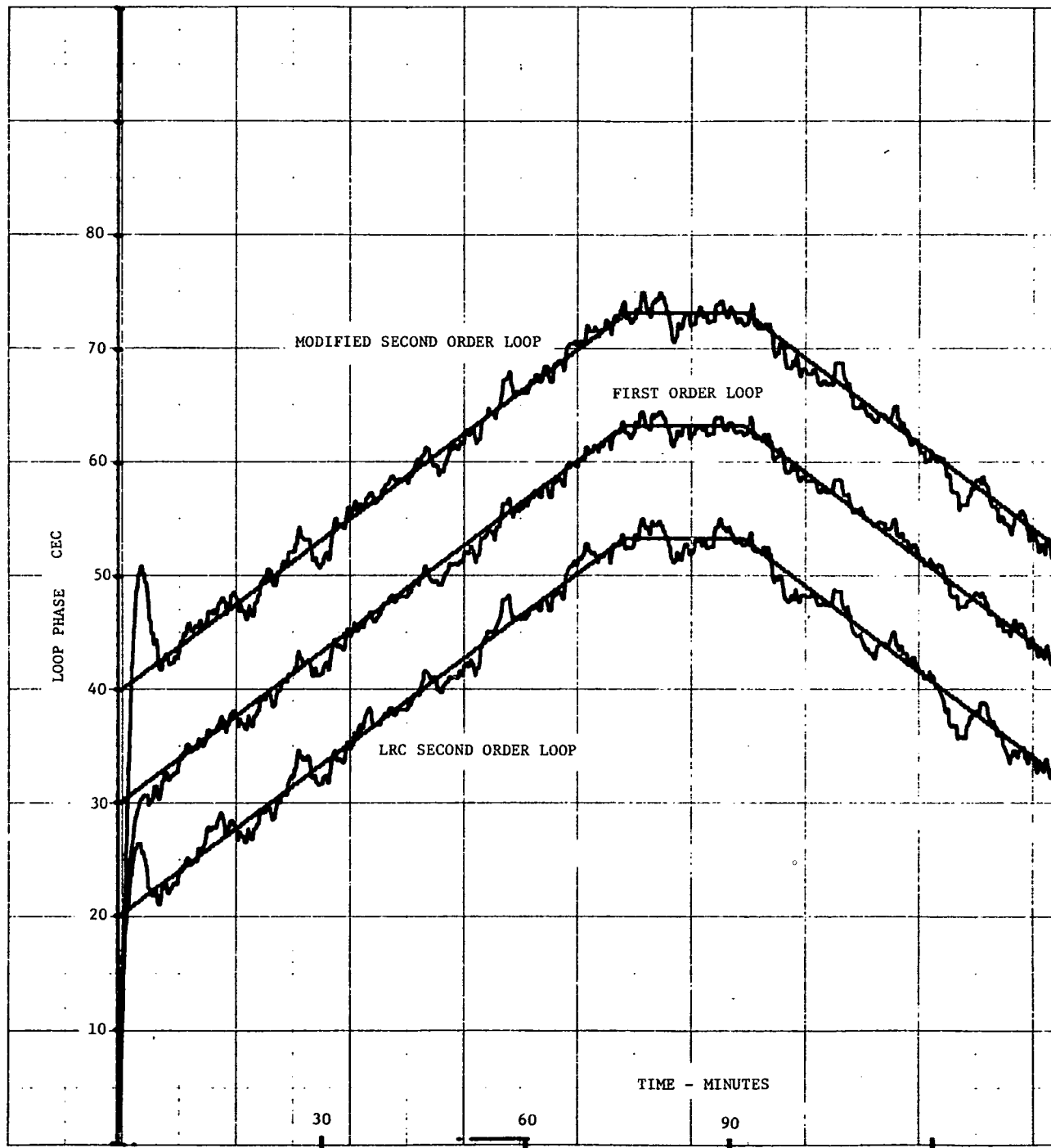


Fig. D-11. Digital phase-locked loop response to input phase ramp of 27 cec/hr with phase jitter standard deviation = 2.5 cec.

of the second order loop is greater than for the first order loop the noisy response of the second order loop is somewhat poorer. Initial lock-in damping is better for the second order loop.

D.3 PLL With Limiter

With a bandpass limiter in front of the phase-locked loop phase detector such that the input signal is limited prior to phase detection the receiver can adapt to varying signal-to-noise input conditions. Output signal-to-noise ratio can be approximated as

$$(\text{SNR})_o = (\text{SNR})_i \frac{1 + 2 (\text{SNR})_i}{4/\pi + (\text{SNR})_i} \quad (\text{D-10})$$

At low $(\text{SNR})_i$ the signal is degraded only by a factor $\pi/4$ and at high $(\text{SNR})_i$ it is enhanced by 3 dB.

Signal voltage delivered to the phase detector will be reduced as noise increases. This reduces the effective phase detector gain and loop gain. Loop bandwidth and damping are also affected. The limiter suppression factor

$$\alpha = \frac{(\text{SNR})_i}{4/\pi + (\text{SNR})_i} \quad \alpha \leq 1$$

will modify the loop gain $K_o K_d$ wherever it appears in the phase-locked loop expressions, consequently affecting other loop parameters.

The modified expressions for the loop natural frequency and damping factor for the second order loop become

$$\omega'_n = \omega_n \sqrt{\alpha} \quad \text{and} \quad \delta' = \delta \sqrt{\alpha} \quad .$$

The noise bandwidth becomes

$$B_L = \frac{\alpha K_o K_d + 1/\tau_1}{4} \quad .$$

With the limiter as input to the phase detector the first and second order loop characteristics are as summarized in Table D-3.

Table D-3. Loop Characteristics with Limiter Input

	Steady State Ramp Error	ω_n	δ	$\alpha K_o K_d$ Gain	N.E. Bandwidth B_L
FIRST ORDER LOOP	$\frac{\Delta\omega}{\alpha K_o K_d}$ Ramp = .01 cec/s $\epsilon = .6127$ cec	$\alpha K_o K_d$		$\alpha K_o K_d$	$\frac{\alpha K_o K_d}{4}$
SECOND ORDER LOOP		$\frac{\alpha K_o K_d}{\tau_1}^{1/2}$	$\frac{(\alpha \tau_1 K_o K_d)^{1/2}}{2}$	$\alpha K_o K_d$	$\frac{\alpha K_o K_d + 1/\tau_1}{4}$
	0	.00203 Hz	.639	.01632	.00658 Hz

Note: Values shown are for $(\text{SNR})_i = 50$ db = 100,000 and $\alpha = .9999$,
Phase Jitter S.D. = 2.5×10^{-6} cec/sec.

Consider the situation as described in Section D.2 where phase jitter has a standard deviation of 2.5 cec corresponding to a limiter output $(\text{SNR})_o = 13.067$ dB. Using (D-10) this yields a corresponding input signal-to-noise ratio to the limiter of

$$(\text{SNR})_i = 10.34 \text{ dB} .$$

In this case the limiter actually enhances the input signal-to-noise ratio by about 2.7 dB. Corresponding loop characteristics are given in Table D-4.

Table D-4. Loop Characteristics with Limiter Input and Noise
 $(\text{SNR})_i = 10.34$ dB, Phase Jitter S.D. = 2.5 cec

LOOP TYPE	α	ω_n	δ	Gain $\alpha K_o K_d$	N.E. BW B_L
FIRST ORDER	.89467	.00233 Hz	-	.01460	.00365 Hz
SECOND ORDER	.89467	.00192 Hz	.6044	.01460	.00615 Hz

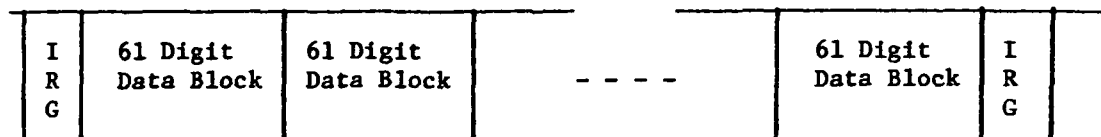
Tables D-3 and D-4 provide PLL characteristics for two ranges of input signal-to-noise ratio. It can be noted that the loop characteristics do not change significantly over this range of input levels.

APPENDIX E

RAW DATA CONVERSION TO PACKED BINARY PHASE READINGS

The raw data tapes created at each receiver site generally contain from 3-5 days of ten-second relative phase readings which are recorded in terms of clock counts. The raw data tapes contain recorded data from both the digital phase-locked loop receiver and the TRACOR 599R receiver in an even parity BCD format at 556 ips (1.412 m/sec). Sixteen relative phase readings, including phase from transmitter stations A, B, C and D at 10.2, 11 1/3 and 13.6 kHz from the PLL receiver and phase from these transmitters at a selected frequency from the TRACOR receiver are recorded on a seven-track, 1/2 inch (1.27 cm) magnetic tape. To complete a logical record of 61 digits, a receiver unit code and a time code with day, hour, minute and second are recorded along with a received signal strength measure to complete the format given in Figure E-1. Eight blocks of identical format (8 10-sec sample points) compose one physical record of 488 digits. Each physical record is separated by an interrecord gap (IRG).

Phase data from the digital PLL receiver are recorded as a number of 4.08 MHz clock counts so that at 10.2 kHz the recorded phase is in the range ± 200 for a 0-100 cec relative phase measure. The 11 1/3 kHz measure is in the range ± 180 counts and the 13.6 kHz measure is in the range ± 150 counts. All phase data are relative to the internal oscillator phase and are measured within one full cycle to the nearest approximately 0.25 cec of 10.2 kHz. The TRACOR receiver phase data are recorded in 408 kHz clock counts. The TRACOR receiver uses a 1 kHz intermediate frequency to represent the phase of the incoming signal (regardless of frequency) so that clock counts are ± 204 representing a 0-100 cec relative phase measure. It should be noted that the sign of the counts which represent the digital PLL phase measure is assigned in the reverse sense from that used for the TRACOR receiver. This point will be discussed in more detail in Section E.2.



8-Data Blocks of 61 Digits Each
Comprise One Logical Record (488 Digits)

Data Block		
Word #	No. of Digits	Content (Note: Sign is in last digit.)
1	3	Norway 10.2 kHz
2	3	Norway 13.6
3	3	Norway 11.3
4	3	Tracor Chan 1 (Norway)
5	3	Trinidad 10.2
6	3	Trinidad 13.6
7	3	Trinidad 11.3
8	3	Tracor Chan 2 (Trinidad)
9	3	Hawaii 10.2
10	3	Hawaii 13.6
11	3	Hawaii 11.3
12	3	Tracor Chan 3 (Hawaii)
13	3	North Dakota 10.2
14	3	North Dakota 13.6
15	3	North Dakota 11.3
16	3	Tracor Chan 4 (North Dakota)
17	3	Signal Strength (Variable Stas.)
18	10	Receiver I. D. Digit Minute - 2 Digits Day - 3 Digits Second - 2 Digits Hour - 2 Digits

Fig. E-1. Digital raw data tape format (7-track tape).

E.1 Packed Binary Format

To provide for statistical analysis of the data, the raw data are converted to phase measurements in centicycles at each respective frequency. New tapes are created during this process and formatted in a packed binary format on a one-for-one basis. The packed binary format provides for three data words per 60-bit computer word so that input to the computer is facilitated, thus minimizing I/O time and required memory for the data. Each phase measurement appears as an integer in the packed form which when unpacked and divided by 100 yields a phase reading in cec, correct to two decimal places.

The packed binary tape is formatted in physical records (block) of at most 512 60 bit binary words. There are from 1 to 34 logical records within each block, one record per sample time. Two words at the beginning of each block identify the tape and the sample time of the last record in the block. All times are in seconds since the beginning of the calendar year plus 86,400 (number of seconds per day). Figure E-2 illustrates this format. This format is used consistently for various forms of the data.

The raw data tape is used directly to create a single station (single receiver station) data tape. The first word contains information in bits 0-4, 5-14, and 30-39 initially according to Table E-1. After the tape is edited, an edit key is inserted in bits 40-43 and in bit 56 of each logical record according to Table E-2.

Table E-1. Single Station Packed Binary Data Tape Identification Word

<u>Word No. 1</u>	<u>Meaning</u>
Bits 0-4	1 - Base Station 2 - Mobile Station #1 3 - Mobile Station #2
Bits 5-14	Tape Number. These are assigned consecutively beginning with 1. The site schedule log must be used to determine the actual receiver position for Stations 2 and 3.
Bits 30-39	Year (Last Two Digits)

BIT 0	4	5	14	15	19	20	29	30	39	40	43	44	54
STATION NO.	TAPE NO.		STATION NO.		TAPE NO.		YEAR		EDIT KEY		OPEN		
SAMPLE TIME OF LAST SAMPLE IN THIS BLOCK													
1 TO 34 LOGICAL RECORDS													

(a) PACKED BINARY TAPE ORGANIZATION

BIT 0	19	20	39	40	59
SAMPLE TIME IN SECONDS SINCE BEGINNING OF YEAR + 86400					
NORWAY	10.2 kHz	NORWAY	13.6 kHz	NORWAY	11.3 kHz
TRINIDAD	10.2 kHz	TRINIDAD	13.6 kHz	TRINIDAD	11.3 kHz
HAWAII	10.2 kHz	HAWAII	13.6 kHz	HAWAII	11.3 kHz
N. DAKOTA	10.2 kHz	N. DAKOTA	13.6 kHz	N. DAKOTA	11.3 kHz
TRACOR	CHAN 1	TRACOR	CHAN 2	TRACOR	CHAN 3
TRACOR	CHAN 4	AMPLITUDE		EDIT KEY (56) AMP KEY (57-59)	
NORWAY-TRINIDAD	10.2 kHz	NORWAY-TRINIDAD	13.6 kHz	NORWAY-TRINIDAD	11.3 kHz
NORWAY- HAWAII	10.2 kHz	NORWAY-HAWAII	13.6 kHz	NORWAY-HAWAII	11.3 kHz
NORWAY-N. DAKOTA	10.2 kHz	NORWAY-N. DAKOTA	13.6 kHz	NORWAY-N. DAKOTA	11.3 kHz
TRINIDAD-HAWAII	10.2 kHz	TRINIDAD-HAWAII	13.6 kHz	TRINIDAD-HAWAII	11.3 kHz
TRINIDAD-N. DAKOTA	10.2 kHz	TRINIDAD-N. DAKOTA	13.6 kHz	TRINIDAD-N. DAKOTA	11.3 kHz
HAWAII-N. DAKOTA	10.2 kHz	HAWAII-N. DAKOTA	13.6 kHz	HAWAII-N. DAKOTA	11.3 kHz
TRACOR	CHAN 1 - CHAN 2	TRACOR	CHAN 1 - CHAN 3	TRACOR	CHAN 1 - CHAN 4
TRACOR	CHAN 2 - CHAN 3	TRACOR	CHAN 2 - CHAN 4	TRACOR	CHAN 3 - CHAN 4

All values are integer, e.g., 99.87 carried as 9987.
 OPEN areas are not currently assigned bits.
 Tapes are written and read as unformatted.

(b) LOGICAL RECORD

Fig. E-2. Format for packed data.

Table E-2. Data Bits For Editing

<u>Word No. 1*</u>	<u>Meaning</u>
Bit 40	1 - Norway Transmitter Operating; 0 - Norway Down
Bit 41	1 - Trinidad Transmitter Operating; 0 - Trinidad Down
Bit 42	1 - Hawaii Transmitter Operating; 0 - Hawaii Down
Bit 43	1 - N. Dakota Transmitter Operating; 0 - N. Dakota Down

Word No. 7 of Each Logical Record

Bit 56	0 - Record Contains No Bad Data; 1 - Record Contains Some Bad Data
Bits 57-59	0 - Norway, 1 - Trinidad, 2 - Hawaii, 3 - North Dakota

*If all bits are 0, tape has not been edited.

The single station packed binary tape format is also used for special skywave correction data which have been obtained for each receiver station (see Appendix G) and calculated for each ten second sample. These data tapes use the same header information as in Table E-1 except that bits 0-4 of block word number one are 10, 20, or 30 depending on whether the corrections apply to data taken at the base station, mobile Station #1, or mobile Station #2, respectively.

The data of the packed binary tapes from individual receiver stations can be merged with other data or with skywave corrections either in edited form or non-edited form. The format of the packed binary tape does not change; however, the information in the block header of the newly created merged tapes is modified to reflect the contents of the tape. Table E-3 shows the information content of block word number 1 of a merged packed binary data tape created by subtracting each data word of the packed binary tape associated with the second station identified from the corresponding data word of the first station identified. The bits assigned for use as editing keys are set at the time merging takes place provided that the individual tapes have been edited. The bits in the block header

word number one are set only if both individual tapes have data taken with each transmitter on the air according to Table E-2. The record edit key of bit 56 word 7 is set if either tape has bad data in that record. A bad data word on either individual tape will cause a bad data word to be indicated on the merged tape.

Table E-3. Merged Packed Binary Data Tape Identification Word

<u>Word No. 1</u>	<u>Meaning</u>	
Bits 0-4	1 - Base Station	} Copied from first single station tape.
	2 - Mobile Station #1	
	3 - Mobile Station #2	
Bits 5-14	Tape Number from First Single Station Tape	
Bits 15-19	1 - Base Station	} Copied from second single station tape.
	2 - Mobile Station #1	
	3 - Mobile Station #2	
Bits 20-29	Tape Number from Second Single Station Tape	

A second category of merged tapes results from adding data from a single station tape to data from a skywave correction tape. The information in the merged binary packed tape block header word number 1 will be created according to Table E-3 with the station identification number of the second tape being either 10, 20, or 30 instead of 1, 2, or 3.

A third category of merged tapes is created from two previously created merged tapes. This would occur, for example, when merging two skywave corrected packed binary tapes. The resulting merged packed binary tape will have station number identifiers 11, 21 or 31 for station 1 corrected, station 2 corrected, or station 3 corrected, respectively. When the tapes to be merged have been edited, the resulting edited merged tape conforms to the format previously described.

E.2 Conversion of Raw Phase Data To Centicycles

The output of the digital phase-locked loop receiver is phase information from each transmitter station at each frequency in counts of the 4.08 MHz clock. The individual phase measurements are relative to internally generated square-wave signals at 10.2, 11 1/3, and 13.6 kHz derived from a 8.16 MHz local oscillator. In the Tracor receiver a 1 kHz intermediate frequency square wave is locked to received phase for each channel and this is compared to a 1 kHz square wave from the local oscillator. Phase comparison is in counts of 408 kHz clock pulses.

The method for determining phase is essentially the same in each receiver. Phase measurement in counts is derived by comparing positive half cycles of two square waves at the same frequency. Figure E-3 illustrates the situations which can occur. In Figure E-3(a) the reference signal is shown. In Figure E-3(b) the loop signal (synchronized to the received signal) is shown in phase with the reference signal. In Figure E-3(c) the loop signal is lagging the reference signal and in Figure E-3(d) the loop signal is leading the reference signal. The shaded region illustrates the coincidence measurement interval. Clock counts are accumulated in a counter which represents the degree of coincidence of the loop signal and the reference signal. The sign of the number of counts is assigned according to whether the loop signal is leading or lagging the reference signal. The sign convention used with the digital phase-locked loop receiver is reversed from that used with the Tracor receiver. The counter outputs are recorded at 10 second intervals.

E.2.1 Digital phase-locked loop receiver (PLL).— In each digital PLL, comparison of positive half cycles yields a number, N_f , where

$$0 \leq |N_f| \leq \frac{1}{2} \left\{ \frac{4.08 \times 10^6}{\text{Freq}} \right\} \quad (\text{E-1})$$

and the frequency is either 10.2, 11 1/3, or 13.6 kHz. If the loop estimate of the received signal is as is shown in Figure E-3(b) there is no phase difference and

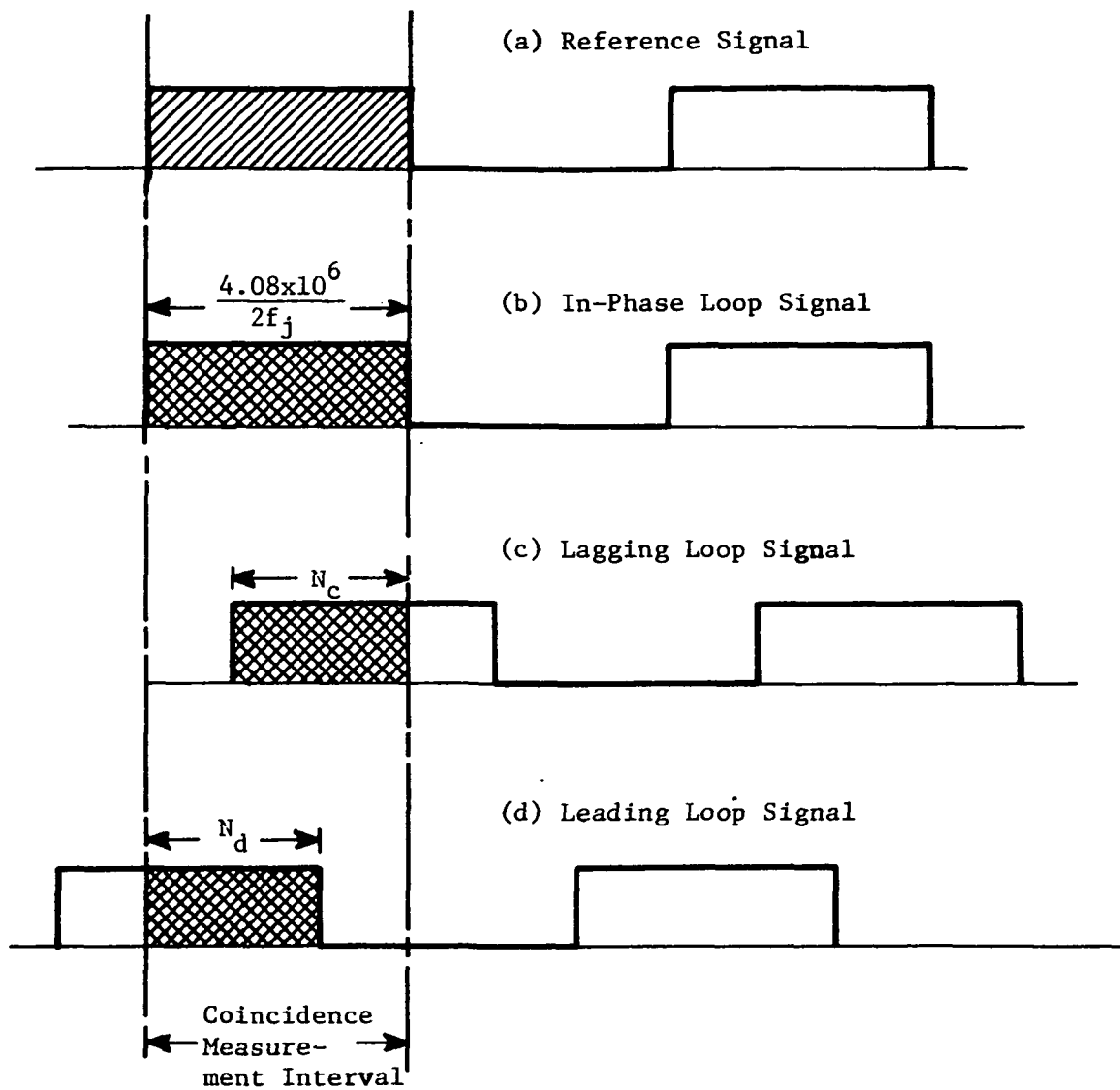


Fig. E-3. Counting relative phase of loop signal.

$$N_{f_j}^{(b)} = \pm \frac{1}{2} \left\{ \frac{4.08 \times 10^6}{f_j} \right\}$$

where f_j ($j = 1, 2$ or 3) is the frequency of the received signal. If the loop signal is lagging the reference as in Figure E-3(c) then

$$0 \leq N_{f_j}^{(c)} \leq + \frac{1}{2} \left\{ \frac{4.08 \times 10^6}{f_j} \right\} ,$$

i.e., the sign of the counts is positive. If the loop signal is leading as in Figure E-3(d) then

$$- \frac{1}{2} \left\{ \frac{4.08 \times 10^6}{f_j} \right\} \leq N_{f_j}^{(d)} \leq 0 ,$$

i.e., the sign of the counts is negative.

To obtain a phase reading from the signed counter value N_f in cec at the given frequency

$$\Delta\phi_j = 50 - \frac{N_{f_j}}{r_j} \quad (E-2)$$

where $r_j = \left\{ \frac{4.08 \times 10^6}{100 \times f_j} \right\}$

and $\Delta\phi_j$ is the phase lag of the loop signal relative to the reference signal in the range $0 \leq \Delta\phi_j = 100$. The j subscript indicates frequency and the r_j values are given in Table E-4.

Table E-4. Phase Measurement Counts Per cec of Phase for Each OMEGA Frequency using 4.08 MHz Clock

<u>j =</u>	<u>Freq. (f_j)</u>	<u>r_j</u>
1	10.2 kHz	4
2	11 1/3 kHz	18/5
3	13.6 kHz	3

Counter	-40	-80	-120	-160	-200,	+200	+160	+120	+80	+40	0, -0	-40	-80	-120	-160
$\Delta\phi$ cec	60	70	80	90	100,	0	10	20	30	40	50	60	70	80	90
a) 10.2 kHz Readings															
	in phase				reference leads										
Counter	-36	-72	-108	-144	-180,	+180	144	108	72	36	0, -0	-36	-72	-108	-144
$\Delta\phi$ cec	60	70	80	90	100,	0	10	20	30	40	50	60	70	80	90
b) 11 1/3 kHz Readings															
	in phase				reference leads										
Counter	-30	-60	-90	-120	-150,	+150	120	90	60	30	0, -0	-30	-60	-90	-120
$\Delta\phi$ cec	60	70	80	90	100,	0	10	20	30	40	50	60	70	80	90
c) 13.6 kHz Readings															
	in phase				reference leads										

Table E-5. Illustration of Relationships between Digital PLL Output Counter Readings in Centicycles of Phase Lead of Reference Signal for a) 10.2 kHz, b) 11 1/3 kHz, and c) 13.6 kHz.

Table E-5 illustrates the relationship between counter readings and centicycles of phase lead of the loop signal at each frequency.

To obtain phase differences or LOP phase measurements for a given station pair i, j , let $\delta\phi_k(i,j)$ be the phase of station i minus the phase at station j at some frequency k . Then

$$\begin{aligned}\delta\phi_k(i,j) &= \phi_k(i) - \phi_k(j) & (E-3) \\ &= [\phi_k(c) - \text{REF}] - (\phi_k(j) - \text{REF}) \\ &= \Delta\phi_k(i) - \Delta\phi_k(j)*\end{aligned}$$

where $\Delta\phi_k(i)$ and $\Delta\phi_k(j)$ are found as in (E-2). Expressing (E-3) in terms of phase counts

$$\delta\phi_k(i,j) = \frac{N_{f_k}(j) - N_{f_k}(i)}{r_k} \quad (E-4)$$

where $-100 \leq \delta\phi_k(i,j) \leq 100$. It should be noted here that even though these phase differences cover a two cycle range, the represented phase is in the range 50 cec lagging to 50 cec leading. Thus $\delta\phi_k(i,j) = 75$ is the same phase relationship as $\delta\phi(i,j) = -25$, i.e., station i phase lagging station j phase by 75 cec is the same condition as station i phase leading station j phase by 25 cec.

E.2.2 Tracor receiver.— In the Tracor 599R receiver the phase coincidence counter reading records counts of a 408 kHz clock. Since all measurements are made at the 1 kHz intermediate frequency which is

*Note that LOP phase difference is a positive measure of relative phase lag in physical terms.

phase coherent to the OMEGA signal at the selected received frequency the measured relative phase is

$$\Delta\phi_j = 50 + \frac{N_f}{r_j} \quad (E-5)$$

where $N_f > 0$ if the received signal leads the reference signal and $N_f < 0$ if the received signal lags the reference signal. With the Tracor receiver $0 \leq |N_f| \leq 204$ where 204 clock counts represent 50 cec of phase and $r_j = 204/50$ regardless of the OMEGA frequency selected and the phase $\Delta\phi_j$ in (E-5) is in cec at the frequency selected.

In the 599R receiver if the received signal phase leads the reference then the coherent 1 kHz signal is made to lag the reference, i.e., the coherent signal is actually phase inverted from the received signal. This in effect changes the meaning of the sign of the counts although the method of counting phase difference and determining the sign of the phase counts is the same as for the digital PLL receiver. This phase inversion of the intermediate frequency in the Tracor receiver is responsible for the sign difference in (E-5) and (E-2). When computing LOP phase differences as in (E-3) with the Tracor data the LOP of station i minus station j becomes

$$\delta\phi_k(i,j) = \frac{N_{f_k}(i) - N_{f_k}(j)}{204/50} \quad (E-6)$$

where the number of counts associated with each transmitter can be subtracted in order and scaled. Again in (E-6), $-100 \leq \delta\phi_k(i,j) \leq 100$ cec at the OMEGA frequency selected.

E.2.3 LOP phase measurement.— The LOP phase measurement using data from the digital PLL receiver is obtained using (E-4) whereas using the Tracor data (E-6) is used. To obtain a unique representation of this phase measure the range should be changed so that 100 cec of phase variation are uniquely represented. This would be done if any analysis or plots of the data were to be made. To scale the data on a range (0, 100) cec

$$\delta\phi'_k(i,j) = \{\delta\phi_k(i,j) + 100\} \bmod 100.$$

To scale the data on a range (-50, + 50) cec

$$\delta\phi''_k(i,j) = \{\delta\phi_k(i,j) + 100\} \text{ if } \delta\phi_k(i,j) \leq -50$$

$$\delta\phi''_k(i,j) = \{\delta\phi_k(i,j) - 100\} \text{ if } \delta\phi_k(i,j) > 50$$

$$\delta\phi''_k(i,j) = \{\delta\phi_k(i,j)\} \quad \text{otherwise.}$$

E.2.4 Difference of LOP phase measurements.— On merged packed binary tapes resulting from two packed binary data tapes, whether skywave corrected or not, each data word in the format is the result of subtracting the corresponding words of the second designated data tape from the first designated data tape. This yields phase data which represent in words 2-6 and word 7 field 1 the difference in relative phase measurement of a given transmitted signal between two receiver stations. In words 8-15 the merged data represent differences in LOP measures at two different receiver stations. This is the differential OMEGA type data, but is on a range of (-100, +100) cec at each frequency. To enable analysis of these data each data word is scaled so that resultant phase variations are in the range (-50, +50) cec about the true value. The true value represents the difference in chart LOP of the two receiver stations or some other suitably defined value.

To scale the data for analysis the LOP phase measurement difference is first scaled by the true value yielding

$$\Delta\phi_{\text{LOP}} = \Delta\phi'_{\text{LOP}} - \Delta\phi_{\text{TRUE}}$$

where $\Delta\phi'_{\text{LOP}}$ is the data LOP difference. The variable $\Delta\phi_{\text{LOP}}$ may now be in the range $-200 \leq \Delta\phi_{\text{LOP}} \leq +200$ cec and is scaled to (-50, +50) cec using

$$\Delta\phi_{LOP}'' = \{\Delta\phi_{LOP}'\} \bmod 100$$

and
$$\Delta\phi_{LOP}''' = \Delta\phi_{LOP}'' - 100 \text{ if } \Delta\phi_{LOP}'' > 50$$

or
$$\Delta\phi_{LOP}''' = \Delta\phi_{LOP}'' + 100 \text{ if } \Delta\phi_{LOP}'' \leq -50$$

or
$$\Delta\phi_{LOP}''' = \Delta\phi_{LOP}'' \text{ if } -50 < \Delta\phi_{LOP}'' \leq 50.$$

Under the assumption that the resulting variable $\Delta\phi_{LOP}'''$ does not vary from the true value more than one-half cycle (50 cec) then any statistical analyses will be valid.

For normal differential OMEGA analysis this procedure is used where corresponding times on the two packed tapes are matched to the nearest 10 second sample point. To obtain data on time correlation, data sample times are displaced in time before LOP phase differences are calculated.

E.2.5 Phase value for edited data.— Whenever data words on a packed binary tape are to be edited out, the corresponding phase measure is changed to -500 which is outside the normal range of any meaningful phase data. Bit 56 of word #7 in a logical record which contains any data word of - 500 is set so that during analysis of the data each data word in that record is checked and, if found to contain -500, is neglected. Appendix F describes the data editing program used to edit the packed binary tapes. Data editing is accomplished using the single station packed binary tapes.

APPENDIX F

DATA EDITING PROCEDURE FOR OMEGA PACKED TAPES

Currently the OMEGA raw data tapes taken from each receiver tape recorder are reformatted and rewritten creating a packed binary tape for each data period (normally 2-4 days). The packed binary tapes contain relative phase readings in centicycles of the particular frequency at which phase is measured. Additionally each packed tape contains phase differences between all possible transmitter pairs (LOP phase). Also included are quantitative measures of received signal strength of each OMEGA signal taken from the Tracor receiver, one transmitter each ten seconds and repeated every fourth record. From the individual packed binary tapes, merged packed tapes are also created, as desired. For example, to evaluate side-by-side receiver performance (repeatability) the packed data for each receiver are merged for the time of the side-by-side test. This merged packed data tape uses the same format as the individual packed tapes. The data represent the difference in cec between the two receiver measurements. Merged packed tapes may also be created for situations where the two receivers are not at the same location. The resulting tape will then contain the differential error plus the nominal phase difference between receivers. (Note that nominal phase difference between receivers is the charted phase difference between receiver locations and is zero if the receivers are at the same location.) Other merged tapes may be desired which involve combining two individual receiver tapes taken at different times to facilitate time correlation studies of differential error. The format for these packed tapes is described in Section E.1 of Appendix E.

In order that the analysis include only valid data, some editing is necessary. Invalid data can result from many circumstances. On the gross scale, transmitters may simply not be operational as is Hawaii (Station C) presently and was Norway (Station A) for the early part of the data gathering period. On the smaller scale, transmitters sometimes may experience short term outages as was experienced on September 23 at North Dakota (reference telephone conversation of September 28, 1973, with Cmdr. J. D. Richardson, Project Manager,

Omega Project Office (NESC), when lightning strikes caused the transmitter to stop for several brief periods). At other times the receivers may lose "lock" for any of a variety of reasons. Also there may be errors in the digital tape recording which occur sporadically. Some data editing is necessary so that the statistical analyses are valid.

To obtain the most objective editing the computer could certainly be employed for this function. However, the task of analytically discriminating between valid and invalid data can often be such a complex task that some visual "human" editing is necessary. It is apparent that experience and judgement are often involved when determining whether certain data are valid. Machine editing will be accomplished on a first pass to eliminate easily formulated bad data characteristics. Visual editing of time history plots will follow to complete the task.

To accomplish data editing, plots of the individual packed tape will be made for all times, frequencies, and transmitter stations of interest. Normally plots of each LOP measure at each receiver site for each frequency and selected plots of merged data for a given transmitter at a given frequency will suffice. A computer program designed to determine instantaneous shifts that appear in the recorded data greater than a specified value will be used to list all occurrences. These shifts are not possible in the receiver and will be edited out. Using this list, a visual inspection of time histories will be made to determine if there are other periods of data that should be disregarded. As a result of this procedure a syllabus of time periods by station and frequency for each bad data segment will be provided as input to the data editing program.

The editing will be completed by changing the appropriate data words of packed tapes by inserting $-500_{(10)}$ in each bad data sample position to indicate that the particular data word should be ignored upon analysis. The following paragraphs describe the computer programmed procedure for accomplishing this purpose.

F.1. Tape Format

The block header information would be appended to include information in bits 40-43 of Word #1 which were previously unused. On an unedited packed tape bits 40-59 of Word #1 of each physical record (logical block) are zero.

When editing is done bits 40-43 will reflect a bit set (1) in each bit position corresponding to a transmitter being operational according to the following table.

<u>Bit Position</u>	<u>Station</u>	<u>Bit Value</u>
40	Norway	0 if not operational, 1 if operational
41	Trinidad	-Same-
42	Hawaii	-Same-
43	N. Dakota	-Same-

This scheme allows a very simple check of whether any particular packed data tape has been edited. If bits 40-43 are all zero no editing has been done.

Any analysis program can then check the appropriate bits of the block header Word #1 and cause printout of the fact that any station or stations are not transmitting at the time the data were gathered. This will accommodate the gross situation.

In each record data words which are to be neglected according to the editing syllabus will be indicated by time, station, and frequency on a data card to the editing program. These data words will then be replaced with the number $-500_{(10)}$ which is outside the range of the data. At the same time an indicator bit in the record will be set to indicate to the analysis program that the record contains data to be neglected. This will enable the analysis program subsequently using the edited data to check data in only those records which contain some bad data. It is estimated that the great majority of records will not contain data to be neglected.

Bit 56 Word #7 in each logical record is set to indicate that the record contains data to be neglected. This segment normally contains signal amplitude information in bits 57-59. For a good record bit 56 is normally zero. For a record containing some bad data the amplitude information will be modified by adding $8_{(10)}$ to the third 20 bit segment of Word #7 to set bit 56.

Following is a description of the input data to the editing program:

<u>Data Card</u>		<u>Contents</u>
1	COLS 1-5	Tape Number of individual tape to be edited or first tape of a merged tape to be edited (ex. 1.32) using an F5.2 format
	COLS 6-10	Tape Number of second tape number of a merged tape to be edited. If editing of an individual tape is to be done this field is blank (F5.2 format)
	COLS 11-18	Station number(s) of transmitter station(s) that is(are) operational. 1-Norway, 2-Trinidad, 3-Hawaii, 4-N. Dakota. If station(s) is(are) not operational leave blank. Each number is format I2 with cols 11-12, Norway, cols 13-14, Trinidad, cols 15-16 Hawaii, and cols 17-18 N. Dakota.
2-end	COLS 1-11	Indicate time period (discrete and non-overlapping) that data words are to be flagged. cols 1-3 day - format I3 cols 4-5 hour - format I2 col 6 blank cols 7-8 beginning minute of segment - format I2 col 9 blank cols 10-11 ending minute of segment - format I2
	COLS 12-27	Station and frequencies to be flagged are indicated by 'X' in appropriate column as follows

<u>Col</u>		
12	Norway	10.2
13	Norway	13.6
14	Norway	11 1/3
15	Trinidad	10.2
16	Trinidad	13.6
17	Trinidad	11 1/3
18	Hawaii	10.2
19	Hawaii	13.6
20	Hawaii	11 1/3
21	N. Dakota	10.2
22	N. Dakota	13.6
23	N. Dakota	11 1/3
24	Tracor	1
25	Tracor	2
26	Tracor	3
27	Tracor	4

F.2 The Data Editing Program

Figure F-1 provides a listing of the data editing program. The program has as input the time periods by station and frequency to be flagged. A packed binary tape is read and written onto a second packed tape with the appropriate changes incorporated. The unedited packed tape can then be removed from the tape library as desired.

There should be a separate data card for each time segment to be flagged. Time segments can be up to one hour long and can not be overlapping. The beginning and ending minutes are inclusive.

Figure F-2 illustrates a sample sequence of data cards which might be provided as input to the edit program.

In creating a merged packed edited tape either of two procedures is available. The individual packed tapes can be edited and then merged with each flagged data word of either tape resulting in a flagged value on the merged tape. An alternate procedure allows for the merged packed tape to be edited directly.

An input data sorting program is available which will have as input data cards in the format specified for the data editing program (see ref. 29). The sorting program will repunch these cards chronologically with non-overlapping time periods in a form as required by the data editing program. Therefore data for two individual tape editing runs can be sorted by computer before being used as input to the editing program to edit a merged packed tape.

As output of the data editing run a listing is provided of all time periods (by station and frequency) which contain flagged data on the edited tape. Also the modified block header Word #1 is listed in octal.

The editing program should request 400 seconds of CDC run time, 40000 words of core storage and 6000 o/s calls.

Skywave Corrected Data

A second file on each packed data tape will contain the same data as on the file described except that specially published skywave corrections for the specific receiver location will be added to each data sample (Appendix G). For each sample of bad data ($-500_{(10)}$) no correction will be added so that analysis of the skywave corrected data will be consistent with the uncorrected data.

**Fig. F-1. Data editing program listing
and flow chart**

```

PROGRAM EDTAPE(TAPE10,TAPE11,OUTPUT,INPUT,
. TAPE5=INPUT,TAPE6=OUTPUT)
INTEGER PKT(7), BUF(512), EOFT, FLD
COMMON NCOUNT, IDAY, IHR, IMIN, JMIN, ITIME(512), IXS(512)
COMMON/FLG/ IPT(3), IW, IFD, INDX, PKT, BUF
COMMON/GENERAL/ IERR, IEND
COMMON/GROSS/ STAPE(2), ISTUP(4)
COMMON/DELETE/ ISTART, IENDTM, ISTFQ(16)
DATA XSECD/86400./, XSECH/3600./, XSECM/60./
C***** THIS PROGRAM IS TO EDIT PACKED SINGLE AND DIFFERENCE TAPES.
IENDTM= 0
IERR=0
IEND=0
CALL GETCRD(STAPE,ISTUP)
PRINT 6000, STAPE
6000 FORMAT (I11, 51X, *RESULTS OF THE EDITING RUN FOR*, /, 53X,
1 *RECEIVER(S) *, 2F6.2, //)
C***** CALL GSEDIT TO CHANGE HEADER-RECS IF NEEDED.
CALL GSEDIT
PRINT 700, PKT(7)
700 FORMAT(* OUTPUT FILE HEADER:*022)
IF (IERR .EQ. 1) GO TO 1000
100 IF (INCARD(ISTFQ) .EQ. 0) GO TO 950
110 CONTINUE
XTM=(FLOAT(IDAY)*XSECD)+(FLOAT(IHR)*XSECH)
START= XTM+(FLOAT(IMIN)*XSECM)
ENDTM= XTM+ (FLOAT(JMIN)*XSECM) + 60.
ISTART=START
IENDTM=ENDTM
PRINT 6010, IDAY, IHR, IMIN, JMIN, ISTFQ
6010 FORMAT(/, * EDIT:*, I5, I3, * --*, 2I3, 5X, (*16A1, *)*)
C**** CALL EDIT TO FLAG THESE STAT-FREQS WITH -500.
CALL EDIT
IF (IERR .EQ. 1) GO TO 1000
IF (IEND .EQ. 1) GO TO 1000
GO TO 100
950 PKT(4)= 430*86400
IF (EOFT(PKT, BUF) .NE. 0) GO TO 970
GO TO 1000
970 PRINT 6020
6020 FORMAT (/, *TAPE COPY ERROR*)
1000 REWIND 10

REWIND 11
STOP
END

```

```

SUBROUTINE GSEDT
  DIMENSION CKTAPE(2), INFO(5), INAME(4)
  INTEGER PKT(7), BUF(512), EOFT, FLD, HEADER
  COMMON/GENERAL/ IERR, IEND
  COMMON/GROSS/ STAPE(2), ISTUP(4)
  COMMON/FLG/ IPT(3), IW, IFD, IND, PKT, BUF
  DATA INAME/3HNOR, 3HTRI, 3HHAW, 3HNOK/
  C**** CHECK ISTUP TO SEE IF AT LEAST ONE STATION IS UP.
  DO 100 I=1,4
    IF (ISTUP(I) .NE. 0) GO TO 200
  100 CONTINUE
  PRINT 6000
  6000 FORMAT (//,5X,*INPUT SAYS THAT NO STATS WERE ON. ERROR*)
  GO TO 990
  C***** INITIALIZE PKT TO SELECT 1ST. HEADER RECORD.
  200 PKT(1)=10
  PKT(2)=-1
  PKT(3)=0
  PKT(4)=0
  PKT(5)= 1
  PKT(6)=11
  INFO(2)=INFO(3)=INFO(4)=INFO(5)=0
  READ (10) BUF
  REWIND 10
  C***** UNPACK TAPE-NOS. AND FIELDS 40-43 FOR HEADER-CHECK.
  IST1= FLD(0, 5, BUF(1))
  ITP1= FLD(5, 10, BUF(1))
  IST2= FLD(15, 5, BUF(1))
  ITP2= FLD(20, 10, BUF(1))
  INFO(1)= FLD(30, 10, BUF(1))
  CKTAPE(1)= FLOAT(IST1) + .01* FLOAT(ITP1)
  CKTAPE(2)= FLOAT(IST2) + .01* FLOAT(ITP2)
  IF (IFIX(STAPE(1)*100.+0.5) .NE. IFIX(CKTAPE(1)*100.+0.5))
    GO TO 950
  IF (IFIX(STAPE(2)*100.+0.5) .NE. IFIX(CKTAPE(2)*100.+0.5))
    GO TO 950
  C**** SET A 1-BIT FOR EACH STATION THAT'S UP.
  PRINT 6002
  6002 FORMAT (//,5X, *THE FOLLOWING STATIONS WERE UP*)
  DO 400 IFL=1,4
    DO 390 IST=1,4
      IF (ISTUP(IFL) .EQ. 0) GO TO 400

      IF (ISTUP(IFL) .NE. IST) GO TO 390
      INFO(IST+1)=1
      PRINT 6003, INAME(IST)
  6003 FORMAT (//,5X,A3)
      GO TO 400
  390 CCATINUE
  C**** IF ISTUP NOT= C-4, HAVE AN INPUT ERROR.
  PRINT 6005, ISTUP(IFL)
  6005 FORMAT (//,5X, *STAT-UP CODE INVALID--*, I2)
  GO TO 990
  400 CONTINUE
  BUF(1)= HEADER(IST1, ITP1, IST2, ITP2, INFO)
  PKT(7)= BUF(1)
  GO TO 1000
  900 PRINT 6009
  6009 FORMAT (//, *AN EOF FOUND AT BEGINNING OF TAPE*)
  GO TO 990
  950 PRINT 6010, STAPE, CKTAPE
  6010 FORMAT (//,5X, *INPUT REC-TAPE-NOS. ARE--*, 2F6.2,
    1 *TAPE REC-TAPE-NOS. ARE--*, 2F6.2)
  990 IERR=1
  1000 RETURN
  END

```

```

SUBROUTINE EDIT
  INTEGER PKT(7), BUF(512), EOFT, FLD, PACK
  DIMENSION KSTAT(5), KFRQ(7), IWD(16), IFLD(16), IDIF(12), IORDER(2,16)
  DIMENSION JORDER(32)
  EQUIVALENCE (IORDER(1), JCROER(1))
  COMMON/GENERAL/ IERR, IEND
  COMMON/DELETE/ ISTART, IENDTM, ISTFQ(16)
  COMMON/FLG/ IPT(3), IW, IFD, INDX, PKT, BUF
  DATA KSTAT/3HNOR, 3HTRI, 3HHAW, 3HNDK, 3HTRC/,
  1 KFRQ/4H10.2, 4H13.6, 4H11.3, 4H1 , 4H2 , 4H3 , 4H4 /,
  2 IDIF/7,8,9, 7,10,11, 8,10,12, 9,11,12/, ICHK/1HX/, IBLK/1H /,
  3 JORDER/1,1, 1,2, 1,3, 2,1, 2,2, 2,3, 3,1, 3,2, 3,3, 4,1, 4,2,
  4 4,3, 5,4, 5,5, 5,6, 5,7/
  C**** CHECK FOR A STATION-NAME MATCH.
  ICNT=0
  DO 300 J=1,16
    IF (ISTFQ(J) .EQ. ICHK) GO TO 100
    IF (ISTFQ(J) .EQ. IBLK) GO TO 300
    PRINT 6003, J, ISTFQ(J)
  6003 FORMAT (/ ,5X, *ERR IN STAT FIELD-* 12, ***, A1)
    GO TO 950
  100 ICNT=ICNT+1
  C**** THE ORDER OF X POINTS TO THE STAT. AND FREQ. AND IORDER-ARRAY
  C PARALLELS THIS TO THE WORD-LOCAT. AND FIELD-LOCAT. ON TAPE.
  IST=IORDER(1,J)
  IFQ=IORDER(2,J)
  IWD(ICNT)=IST
  IFLD(ICNT)=IFQ
  PRINT 6005, KSTAT(IST), KFRQ(IFQ), IWD(ICNT), IFLD(ICNT)
  6005 FORMAT(5X,A3,1X,A4,* ---- WCRD*,I3,* FIELD*,I2)
  C**** IS THIS A TRACOR CHANNEL. IF SO, FIELDS 4,5,6 ARE 1,2,3, AND
  C FIELD 7 IS WORD 6, FIELD 1.
  IF (IFLD(ICNT) .LT. 4) GO TO 300
  IF (IFLD(ICNT) .EQ. 7) GO TO 200
  IFLD(ICNT)=IFLD(ICNT) - 3
  GO TO 300
  200 IWD(ICNT)=IWD(ICNT) + 1
  IFLD(ICNT)=1
  300 CONTINUE
  IMAX=ICNT
  C**** THE CORRESP. WORD AND BIT-FIELD HAVE BEEN FOUND FOR EACH
  C STAT-FREQ THAT NEEDS TO BE FLAGGED.

  C*****
  PKT(4)= ISTART
  390 IF (EOFT (PKT,BUF)) 950,900,400
  400 NTM= PKT(2)
  IF (BUF(NTM) .LT. IENDTM) GO TO 500
  PKT(5)=0
  GO TO 1000
  C**** SET AMP-KEY TO 1 FOR THIS RECORD AND THEN SET FIELD TO -50000.
  500 INDX=PKT(2) + 6
  IPT(1)= FLD(0, 20,BUF(INDX))
  IPT(2)= FLD(20,20,BUF(INDX))
  IPT(3)= FLD(40,20,BUF(INDX))
  CALL TEST
  IF (IPT(3) .LT. 8) IPT(3)= IPT(3) + 8
  BUF(INDX)= PACK(IPT(1),IPT(2),IPT(3))
  MTM= BUF(NTM) - 22809600
  CALL TEST
  C***** SET THE FLAGGED FREQS TO -500, AND REPACK WORD. CALL FLAG.
  DO 850 I=1,IMAX
    IW= IWD(I)
    IFD= IFLD(I)
    INDX=PKT(2) + IW
    CALL TEST $ CALL FLAG $ CALL TEST

```

```

C***** MUST ALSO SET EACH CORRESP. DIFF TO -500.
      DO 600 K=1,4
      IF (IW .GT. 4) GO TO 710
      IF (IW .EQ. K) GO TO 610
600  CONTINUE
      PRINT 6030, IW
6030  FORMAT (//,5X, *WORD-COUNT IS INVALID--*, I3)
      GO TO 950
C***** L POINTS TO THE 1ST POSITION OF THE CORRESP DIFFS.
610  L=(K-1)*3 + 1
      DO 700 M=1,3
      INDX= PKT(2) + 10IF(L)
      CALL TEST          $      CALL FLAG          $      CALL TEST
      L= L+1
700  CONTINUE
      GO TO 800
C***** THIS IS A TRACOR. MUST SET ITS CORRESP DIFFS.
710  IF (IW .EQ. 6) GO TO 750
      IF (IFD .EQ. 1) GO TO 720
      IF (IFD .EQ. 2) GO TO 730

      IF (IFD .EQ. 3) GO TO 740
      PRINT 6040, IFD
6040  FORMAT (//,5X, *FLD-NO. FOR TRACOR INVALID--*, I3)
      GO TO 950
C***** FOR TRC-1, CORRES. DIFFS ARE IN WORD+13, FIELDS 1,2, AND 3.
720  INDX= PKT(2) + 13
      DO 725 IT=1,3
      IFD=IT
      CALL TEST          $      CALL FLAG          $      CALL TEST
725  CONTINUE
      GO TO 800
C***** FOR TRC-2, CORRES. DIFFS ARE IN WORD+13, FLD1, WORD+14, FLDS1,2.
730  INDX= PKT(2) + 13
      IFD=1
      CALL TEST          $      CALL FLAG          $      CALL TEST
      INDX=PKT(2)+14
      CALL TEST          $      CALL FLAG          $      CALL TEST
      IFD=2
      CALL TEST          $      CALL FLAG          $      CALL TEST
      GO TO 800
C***** FOR TRC-3, CORRES. DIFFS ARE IN WD+13, FLD2/ WD+14, FLDS1, 3.
740  INDX=PKT(2)+13
      IFD=2
      CALL TEST          $      CALL FLAG          $      CALL TEST
      INDX=PKT(2)+14
      IFD=1
      CALL TEST          $      CALL FLAG          $      CALL TEST
      IFD=3
      CALL TEST          $      CALL FLAG          $      CALL TEST
      GO TO 800
C***** FOR TRC-4, CORRES. DIFFS ARE IN WD+13, FLD3/ WD+14, FLDS2, 3.
750  INDX= PKT(2)+13
      IFD=3
      CALL TEST          $      CALL FLAG          $      CALL TEST
      INDX=PKT(2)+14
      IFD=2
      CALL TEST          $      CALL FLAG          $      CALL TEST
      IFD=3
      CALL TEST          $      CALL FLAG          $      CALL TEST
800  IF (IERR .EQ. 1) GO TO 1000
      CALL TEST
850  CONTINUE
      GO TO 390

```

```

900 IEND=1
    PRINT 6050, IEND
6050 FORMAT (/, *IEND=*, I2, 5X, *END OF FILE ON INPUT TAPE*)
    GO TO 1000
950 IERR=1
1000 RETURN
    END

```

```

SUBROUTINE FLAG
  INTEGER PKT(7), BUF(512), FLD, PACK
  COMMON/GENERAL/ IERR, IEND
  COMMON/FLG/ IPT(3), IW, IFD, INDX, PKT, BUF
  IPT(1)= FLD(0, 20, BUF(INDX))
  IPT(2)= FLD(20, 20, BUF(INDX))
  IPT(3)= FLD(40, 20, BUF(INDX))
  DO 100 IMT=1, 3
  IF (IFD .EQ. IMT) GO TO 150
100 CONTINUE
  PRINT 6000, IFD
6000 FORMAT (///, 5X, *ERR IN FIELD COUNT IN SBRTN FLAG--*, I3)
  IERR=1
  GO TO 1000
C***** FOUND CORRECT FIELD TO FLAG
150 IPT(IMT)= -50000
  BUF(INDX)= PACK(IPT(1), IPT(2), IPT(3))
1000 RETURN
  END

```

```

SUBROUTINE TEST
  INTEGER PKT(7), BUF(512), EOFT, FLD, PACK
  COMMON/FLG/ IPT(3), IW, IFD, INDX, PKT, BUF
  RETURN
  IPT(1)= FLD(0, 20, BUF(INDX))
  *****
  IPT(2)= FLD(20, 20, BUF(INDX))
  IPT(3)= FLD(40, 20, BUF(INDX))
  PRINT 6000, INDX, IPT
6000 FORMAT (///, 5X, *FOR WORD*, I4, *VALUES=*, 3I10)
  RETURN
  END

```

```

SUBROUTINE GETCRD(STAPE,ISTUP)
COMMON N, IDAY, IHR, IMIN, JMIN, ITIME(512), IXS(512)
DIMENSION STAPE(2), ISTUP(4)
INTEGER PACK, FLC
DIMENSION IX(16), ICMMT(6)
100 READ 100, STAPE, ISTUP
   FORMAT(2F5.2, 4I2)
   PRINT 110
110  FORMAT(*1 INPUT CARD DATA: *, /)
   K=0
200  K=K+1
C
C
C      READ DATA IN THE FOLLOWING FORMAT
C      DAY-HOUR    START MIN.    END MIN.    EDITTING DATA
C
250  READ 300, ITIME(K), II, JJ, IX, ICMMT
300  FORMAT(I5, I1, I2, I1, I2, 16A1, 5A10, A3)
   IF (EOF, 5) 400, 301
C
C      PACK THE TIME AND THE A/N DATA
C      PACK----- THIS FUNCTION PACKS 3 20-BIT VALUES PER WORD
C      NP3X16--- THIS FUNCTION PACKS 16 3-BIT VALUES PER WORD
C
301  CONTINUE
   PRINT 310, ITIME(K), II, JJ, IX, ICMMT
310  FORMAT(I9, * ---*, 2I3, 5X, *[*16A1*]*, 5X, 6A10)
   ITIME(K)=PACK(ITIME(K), II, JJ)
   DO 350 I=1, 16
   IF (IX(I) .EQ. 1H ) GO TO 325
   IX(I)=1
   GO TO 350
325  IX(I)=0
350  CONTINUE
   IXS(K)=NP3X16(IX)
   IF (IXS(K) .EQ. 0) GO TO 250
   GO TO 200
400  N=K-1
C
C      SORT THE DATA IN ASCENDING ORDER BY ITIME
C
   K=N

```



```

      I=0
1100  I=I+1
      IF(I.EQ.K) GO TO 1500
      IF(itime(I) .LE. itime(I+1)) GO TO 1100
      II=itime(I)
      itime(I)=itime(I+1)
      itime(I+1)=II
      II=ixs(I)
      ixs(I)=ixs(I+1)
      ixs(I+1)=II
      J=I
1400  IF(J .EQ. 1) GO TO 1100
      IF(itime(J-1) .LE. itime(J)) GO TO 1100
      II=itime(J)
      itime(J)=itime(J-1)
      itime(J-1)=II
      II=ixs(J)
      ixs(J)=ixs(J-1)
      ixs(J-1)=II
      J=J-1
      GO TO 1400
1500  CONTINUE
      PRINT 1550
1550  FORMAT(*1SORTED INPUT CARD DATA:*)
      DO 1600 I=1,N
      IDAYHR=FLD(0,20,itime(I))      $      IMIN=FLD(20,20,itime(I))
      JMIN=FLD(40,20,itime(I))      $      IIX=FLD(0,48,ixs(I))
1600  PRINT 1650, IDAYHR,IMIN,JMIN,IIX
1650  FORMAT(I9,* ---*,2I3,5X,0I6)
      RETURN
      END

```

```

FUNCTION INCARD(ISTFRQ)
COMMON N, IDAY, IHR, IMIN, JMIN, ITIME(512), IXS(512)
EQUIVALENCE (ISMIN, IMIN), (IEMIN, JMIN)
DIMENSION ISTFRQ(16)
DATA I/1/
INTEGER PACK, FLD
100 IF(I ~ N) 200, 6000, 9000
200 J=I+1
C
C      COMBINE DUPLICATE TIME PERIODS
C
      IF(ITIME(I) .NE. ITIME(J)) GO TO 300
      IXS(J)=IXS(I) .OR. IXS(J)
      I=J
      GO TO 100
300 IDAYHR=FLD(0, 20, ITIME(I))
      ISMIN=FLD(20, 20, ITIME(I))
      IEMIN=FLD(40, 20, ITIME(I))
      IX=IXS(I)
C
C      IF DIS-JOINT TIME PERIODS, RETURN A VALUE
C
      IF(FLD(0, 20, ITIME(J)) .NE. IDAYHR) GO TO 7000
      JSMIN=FLD(20, 20, ITIME(J))
      IF(IEMIN .LT. JSMIN) GO TO 7000
C
C      BRANCH IF IDENTICAL START TIMES
C
      IF(ISMIN .EQ. JSMIN) GO TO 1000
C
C      PROCESSING FOR IDAYHR .EQ. JDAYHR, ISMIN .LT. JSMIN .LT. IEMIN
C      IT SUFFICES TO RETURN THE PERIOD ISMIN, JSMIN-1
C      AND ORDER THE REMAINING PERIODS
C
      ITIME(I)=PACK(IDAYHR, JSMIN, IEMIN)
      IEMIN=JSMIN-1
C      ORDER
C
      K=I
600 IF(K .EQ. N) GO TO 7100
      IF(ITIME(K) .LT. ITIME(K+1)) GO TO 7100
      II=ITIME(K)
      ITIME(K)=ITIME(K+1)
      ITIME(K+1)=II
      II=IXS(K)
      IXS(K)=IXS(K+1)
      IXS(K+1)=II
      K=K+1
      GO TO 600
C
C      PROCESSING FOR IDAYHR .EQ. JDAYHR, ISMIN .EQ. JSMIN, IEMIN .LT. JEMIN
C      IT SUFFICES TO FORM DISJOINT PERIODS
C      AND ORDER THE REMAINING PERIODS
C
1000 IXS(I)=IXS(I) .OR. IXS(J)
      ITIME(J)=PACK(IDAYHR, IEMIN+1, FLD(40, 20, ITIME(J)))
      K=J
1100 IF(K .EQ. N) GO TO 200
      IF(ITIME(K) .LT. ITIME(K+1)) GO TO 200
      II=ITIME(K)
      ITIME(K)=ITIME(K+1)
      ITIME(K+1)=II
      II=IXS(K)
      IXS(K)=IXS(K+1)
      IXS(K+1)=II
      K=K+1

```

```

      GO TO 1100
6000  IDAYHR=FLD(0,20,ITIME(1))
      ISMIN=FLD(20,20,ITIME(1))
      IEMIN=FLD(40,20,ITIME(1))
      IX=IXS(1)
7000  I=I+1
7100  IDAY=IDAYHR/100
      IHR=IDAYHR-IDAY*100
      K=0
      DO 7250 L=1,16
      ISTRQ(L)=1HX
      IF(FLD(K,3,IX).EQ.0) ISTRQ(L)=1H
7250  K=K+3
      INCARD=I
      RETURN
9000  INCARD=0
      RETURN
      END
ING VARIABLES EQUIVALENCED BUT NOT REFERENCED

```

```

      INTEGER FUNCTION EOFT(PKT,BUF)
      INTEGER PKT(7),BUF(512),TIME,TAPE
      DATA LOOP/0/,NFWA/3/,NWPB/512/,NRLT/15/,RLT/15./
C      PKT (1) INPUT TAPE NUMBER
C      (2) STATUS INPUT: - BEGIN SEARCH W/ BLOCK READ-SEARCH
C                        0 INPUT TAPE IS ALREADY SETTING ON EOF
C                        + BEGIN SEARCH W/ RECORD READ-SEARCH
C      OUTPUT: - INVALID (WILL NOT HAPPEN)
C              C EOF DETECTED ON INPUT TAPE
C              + POINTER TO FIRST WORD OF THE NEXT LOGICAL
C                RECORD W/ TIME GE SEARCH TIME
C      N.B. THE FUNCTION VALUE ON RETURN IS THE SAME AS THE STATUS
C      (3) READ BLOCK COUNT
C      (4) SEARCH TIME IN SECONDS SINCE THE BEGINNING OF THE YEAR
C      (5) RE-READ KEY 0 = BEGIN SEARCH W/ LAST LOGICAL RECORD FOUND
C                    +1 = SKIP 1 LOGICAL RECORDS OR TO NEXT PHYSICAL
C                        RECORD (WHICHEVER IS LESS) TO BEGIN
C                        SEARCH (FROM LAST LOGICAL RECORD FOUND)
C      N.B. THIS MAY BE OVERRIDEN BY THE INPUT STATUS
C      (6) OUTPUT TAPE NUMBER; IF NOT POSITIVE, NO OUTPUT IS DONE
C      (7) OUTPUT HEADER REPLACEMENT; IF OUTPUT IS DONE, THE HEADER
C          WORD OF EACH OUTPUT BLOCK IS SET TO THIS VALUE
C      IF(PKT(2)) 300,400,100
100    NDEX=PKT(2)+IFIX(PKT(5)*RLT)
      PKT(5)=1
200    IF(NDEX.GT. 512) GO TO 300
250    IF(BUF(NDEX).GE. PKT(4)) GO TO 600
      NDEX=NDEX+NRLT
      GO TO 200
300    IF(PKT(6).EQ. 0) GO TO 350
      IF(PKT(3).EQ. 0) GO TO 350
      BUF(1)=PKT(7)
      TAPE=PKT(6)
      WRITE(TAPE) BUF

```

```

350  REAC(PKT) BUF
      IF(EOF,PKT) 500,375
375  PKT(3)=PKT(3)+1
      IF(BUF(2) .LT. PKT(4)) GO TO 300
      NDEX=NFWA
      GO TO 250
400  PRINT 450 , PKT
450  FORMAT(* RE-READ EOF: PKT(*,12,214,110,12,13,020,*)*)

      LOOP=LOOP+1
      IF(LOOP .GT. 10) STOP
500  NDEX=0
600  ENFT=PKT(2)=NDEX
      RETURN
      END

```

HEADER STORAGE ALLOCATION.

ADDRESS LENGTH
0 21
21

PIINARY CONTROL CARDS.

IDENT HEADER
END

ENTRY POINTS.

HEADER - 1

HEADER

0	10050104052200000002	TRACE HEADER	IDENT HEADER	418800000
1	000000000000000000		ENTRY HEADER	418900000
2	5110000017 + 56210		VFD 42/6LHEADER, 18/2	419000000
			DATA 3	419100000
			SA1 MASK5	419200000
			SA2 R1	419300000
3	5130000020 + 56220		RX6 X2*X1	419400000
			SA3 MASK10	419500000
			SA2 R2	419600000
4	2061? 12662 56230 11221		SA2 X2*X3	419700000
			LX6 10	419800000
			RX6 X6+X2	419900000
			SA2 R3	420000000
			FX2 X2*X1	420100000
5	20605 12662 56240 11223		LX6 5	420200000
			RX6 X5+X2	420300000
			SA2 R4	420400000
			FX2 X2*X3	420500000
6	20612 12662 56250 11223		LX6 10	420600000
			RX6 X6+X2	420700000
			SA2 R5	420800000
			FX2 X2*X3	420900000
7	20612 12662 5110000016 + 11221		LX6 10	421000000
			RX6 X5+X2	421100000
			SA1 MASK1	421200000
			SA2 R5+1	421300000
10	5125000001 11221 20601		FX2 X2*X1	421400000
			LX5 1	421500000
			RX6 X6+X2	421600000
11	12662 5125000002 11221		SA2 R5+2	421700000
			FX2 X2*X1	421800000

12	20601	12662	1	LX6	SHIFT X6 FOR F1	4219000000
			X6+X2	8X6	.OR. RNA,TNA,RNB,TNB,YR,F0,F1	4220000000
13	11221	5125000003	R5+3	SA2	GET FLAG FOR HAWAII	4221000000
			X2+X1	8X2	.AND.	4222000000
	20601		1	LX6	SHIFT X6 FOR F2	4223000000
			X6+X2	8X6	.OR. RNA,TNA,RNB,TNB,YR,F0,F1,F2	4224000000
14	5125000004	12662	R5+4	SA2	GET FLAG FOR N DAKOTA	4225000000
		11221	X2+X1	8X2	.AND.	4226000000
		20601	1	LX6	SHIFT X6 FOR F3	4227000000

HEADER

COMPASS - VER 2. 08/16/74 10.42.44. PAGE 3

15	12662	20620	8X6	X6+X2	.OR. RNA,TNA,RNB,TNB,YR,F0,F1,F2,F3	4228000000
			LX6	16	SHIFT X6 FOR POSITION	4229000000
16	00000000000000000001	0400000001	EQ	HEADER		4230000000
17	00000000000000000001		DATA	18		4231000000
20	00000000000000000037		DATA	378		4232000000
21	000000000000000001777		DATA	17778		4233000000
			END			4234000000

37400 STORAGE USED
6400 ASSEMBLY

47 STATEMENTS
0.388 SECONDS

5 SYMBOLS
10 REFERENCES

PACK STORAGE ALLOCATION.

COMPASS - VER 2. 08/16/74 10.42.45. PAGE 1

BINARY CONTROL CARDS.

ADDRESS LENGTH IDENT PACK
0 6
6
I=PACK(11,12,13)
END

ENTRY POINTS.

PACK - 1

PACK I=PACK(11,12,13)

COMPASS - VER 2. 08/16/74 10.42.45. PAGE 2

0	20010313000000000003	TRACE	PACK	IDENT PACK	ENTRY PACK	42/4LPACK,18/3	VALUES INTO THE FUNCTION VALUE	ENTRY/EXIT WORD	GET 13 IN X1	GET COMPLEMENT OF 20 BIT MASK	MASK OFF LEFT 40 BITS (RESULT IN X6)	GET 12 IN X1	MASK OFF LEFT 40 BITS (RESULT IN X1)	SHIFT RESULT TO MIDDLE THIRD WORD	FORM INTERMEDIATE RESULT (0,12,13)	GET 11 IN X1	MASK OFF LEFT 40 BITS (RESULT IN X1)	SHIFT RESULT TO LEFT-MOST THIRD WORD	COMPLETE PACKED WORD (11,12,13)	RETURN
1	00000000000000000000			DATA C																
2	56130 43250			SAL B3																
				MX2																
				RX6																
3	15112 20124			SAL B2																
				PK1																
				LX1																
				RX6																
				SAL B1																
4	15112 20152			MX1																
				LX1																
				RX6																
5	0400000001 +			EQ																
6				END																

17400 STORAGE USED 17 STATEMENTS 2 SYMBOLS
6400 ASSEMBLY 0.144 SECONDS 4 REFERENCES

PACK I=PACK(11,12,13)
SYMBOLIC REFERENCE TABLE.

COMPASS - VER 2. 08/16/74 10.42.45. PAGE 3

PACK	1	PROGRAM*	2/02 E	2/04 L	2/16
TRACE	0	PROGRAM*	2/03 L		

```

PROGRAM EDTAPE(TAPE10,TAPE11,OUTPUT,INPUT,
  TAPES=INPUT,TAPE6=OUTPUT)

```

```

INTEGER PKT(7), BUF(512), EOF1, FLD
COMMON NCOUNT, IDAY, IHR, IMIN, ISEC, ITIME(512), IXS(512)
COMMON/FLG/ IPT(3), IW, IFO, INDX, PKT, BUF
COMMON/GENERAL/ IERR, IEND
COMMON/CROSS/ STAPE(2), ISTUP(4)
COMMON/DELETE/ ISTART, IENDTH, ISTE(16)
DATA XSECD/55100./, XSECH/3600./, XSECM/60./

```

```

***** THIS PROGRAM IS TO EDIT PACKED SINGLE AND DIFFERENCE TAPE6.

```

```

IENDTH=0
IERR=0
IEND=0

```

```

CALL
CALL GFCRO(STAPE,ISTUP)

```

```

PRINT 5000, STAPE

```

```

***** CALL GSEDT1 TO CHANGE HEADER-RECS. IF NEEDED.

```

```

CALL
CALL GSEDT1

```

```

PRINT 700, PKT(7)

```

```

F
IF (IERR.EQ.1)

```

```

T
GO
TO
1000

```

```

100

```

```

F
IF (INCRD(ISTH)
0).EQ.0)

```

```

T
GO
TO
990

```

```

110
CONTINUE

```

```

XTH=(FLOAT(IDAY)*XSECD)+(FLOAT(IHR)*XSECH)
START=XTH+(FLOAT(IMIN)*XSECM)
ENDTH=XTH+(FLOAT(IMIN)*XSECM)+50.
ISTART=START
IENDTH=ENDTH

```

```

PRINT 5010, IDAY, IHR, IMIN, ISEC, ITIME

```

```

***** CALL EDIT1 TO FLAG THESE START-VALUES WITH -500.

```

```

CALL
CALL EDIT1

```

```

F
IF (IERR.EQ.1)

```

```

T
GO
TO
1000

```

```

100

```

```

F
IF (IEND.EQ.1)

```

```

T
GO
TO
1000

```

```

100

```

```

GO
TO
100

```

```

GO
TO
100

```

```

GO
TO
100

```

```

GO
TO
100

```

```

GO
TO
100

```

```

GO
TO
100

```

```

GO
TO
100

```

```

GO
TO
100

```

```

GO
TO
100

```

43 PG. 2

```

990
PKT(4)=400+86400

```

```

F
IF (EOF1(PKT,B
UF).NE.0)

```

```

T
GO
TO
970

```

```

GO
TO
1000

```

```

970
PRINT 6020

```

```

1000
REWIND 10
REWIND 11
STOP

```

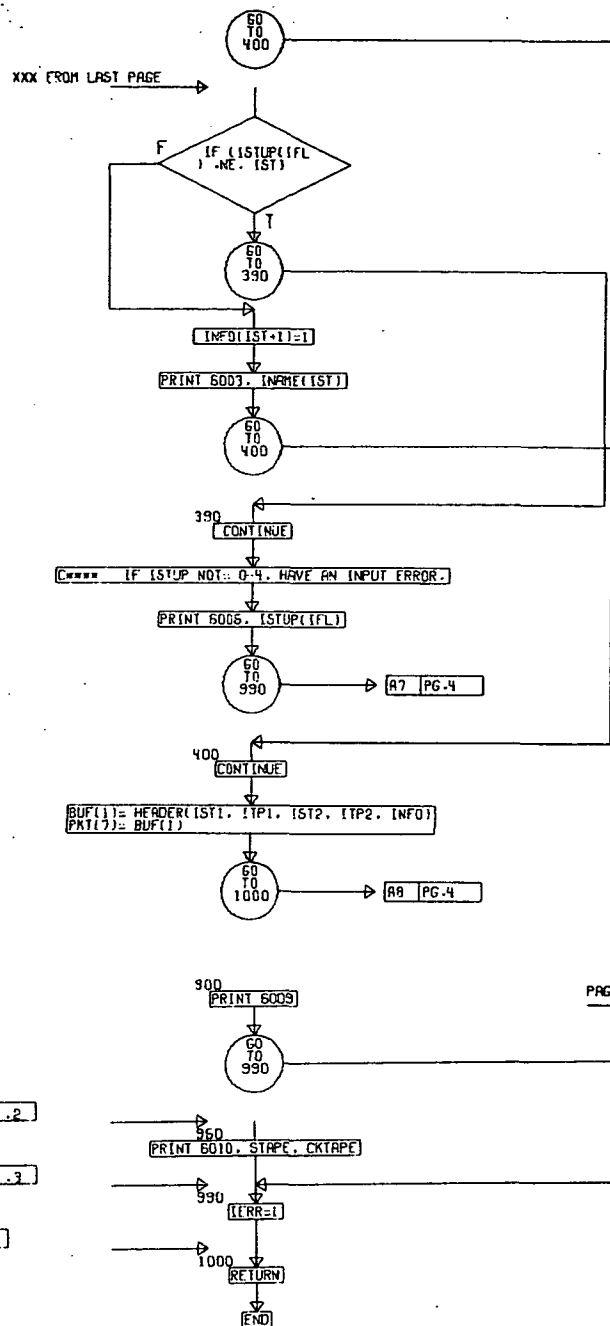
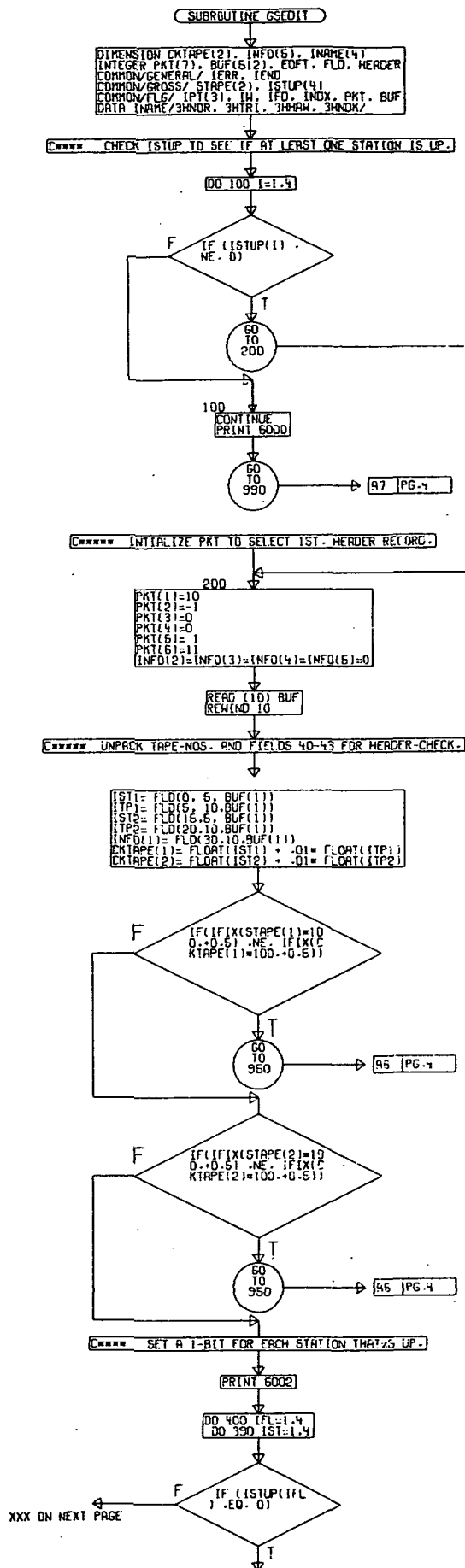
```

ENG

```

44 PG. 1 2 2

41 PG. 2



A5 PG.2 .2

A7 PG.1 .3

A8 PG.3

SUBROUTINE EDIT

```

INTEGER PKT(7), BUF(512), EOFI, FLD, PACK
DIMENSION KSTAT(5), KFRQ(7), IWD(16), IFLD(16), IDIF(12), IORDER(2,16)
DIMENSION JORDER(32)
EQUIVALENCE (IORDER(1), JORDER(1))
COMMON/GENERAL/ IERR (END)
COMMON/DELETE/ ISTART, IENDTH, ISTFQ(16)
COMMON/FLG/ IPT(3), IW, IFD, INDX, PKT, BUF
  
```

DATA KSTAT/3HND, 3HTR1, 3HAW, 3HNDK, 3HTRC/, 4H3
 KFRQ/4H10, 2, 4H13, 6, 4H11, 3, 4H12, 4H2, 4H4
 IDIF/7, 8, 3, 7, 10, 11, 8, 10, 12, 9, 11, 12, 10H/1H/, 1BLK/1H/
 JORDER/1, 1, 2, 1, 3, 2, 1, 5, 2, 2, 3, 3, 1, 3, 2, 3, 3, 4, 1, 4, 2,
 4, 3, 6, 4, 6, 5, 5, 6, 5, 7

***** CHECK FOR A STATION-NAME MATCH.

ICNT=0
 DO 300 J=1,16

F IF (ISTFQ(J) .
 EQ. ICHK)

GO
 TO
 100

F IF (ISTFQ(J) .
 EQ. IBLK)

GO
 TO
 300

A3 PG-2

PRINT 6003, J, ISTFQ(J)

GO
 TO
 900

A13 PG-3

100

ICNT=ICNT+1

***** THE ORDER OF X POINTS TO THE STAT. AND +REQ. AND IORDER-ARRAY
 PARALLELS THIS TO THE WORD-LOCAT. AND FIELD-LOCAT. ON TAPE.

IST=IORDER(1,J)
 IFQ=IORDER(2,J)
 IWD(ICNT)=IST
 IFLD(ICNT)=IFQ

PRINT 6005, KSTAT(IST), KFRQ(IFQ), IWD(ICNT), IFLD(ICNT)

***** IS THIS A TRACOR CHANNEL. IF SO, FIELDS 4,5,6 ARE 1,2,3, AND
 FIELD 7 IS WORD 5, FIELD 1.

F IF (IFLD(ICNT) .
 LT. 4)

GO
 TO
 300

F IF (IFLD(ICNT) .
 EQ. 7)

GO
 TO
 200

IFLD(ICNT)=IFLD(ICNT)-3

GO
 TO
 300

IFWD(ICNT)=IFWD(ICNT)+1
 IFLD(ICNT)=1

300

A3 PG-1

CONTINUE

IMAX=ICNT

***** THE CORRESP. WORD AND BIT-FIELD HAVE BEEN FOUND FOR EACH
 STAT-FREQ THAT NEEDS TO BE FLAGGED.

PKT(4)=ISTART

390

IF (EOFI (PKT,
 BUF)) 960,900,
 400

A18 PG-9

400
 NTM=PKT(2)

F IF (BUF(NTM) .
 LT. IENDTH)

GO
 TO
 500

PKT(5)=0

GO
 TO
 1000

B20 PG-9

***** SET AMP KEY TO 1 FOR THIS RECORD AND THEN SET FIELD TO -50000.

500
 INDX=PKT(2)+8
 IPT(1)=FLD(0,20,BUF(INDX))
 IPT(2)=FLD(20,20,BUF(INDX))
 IPT(3)=FLD(40,20,BUF(INDX))

CALL
 CALL TEST

IF (IPT(3) .LT. 8) IPT(3)=IPT(3)+8
 BUF(INDX)=PACK(IPT(1),IPT(2),IPT(3))
 NTM=BUF(NTM)-22809600

CALL
 CALL TEST

***** SET THE FLAGGED FREDS TO -500, AND REPACK WORD, CALL FLAG.

DO 860 I=1,IMAX
 IW=IWD(I)
 IFQ=IFLD(I)
 INDX=PKT(2)+IW

CALL TEST CALL FLAG CALL TEST

***** MUST ALSO SET EACH CORRESP. DIFF TO -500.

DO 600 K=1,4

F IF (IW .GT. 4)

GO
 TO
 710

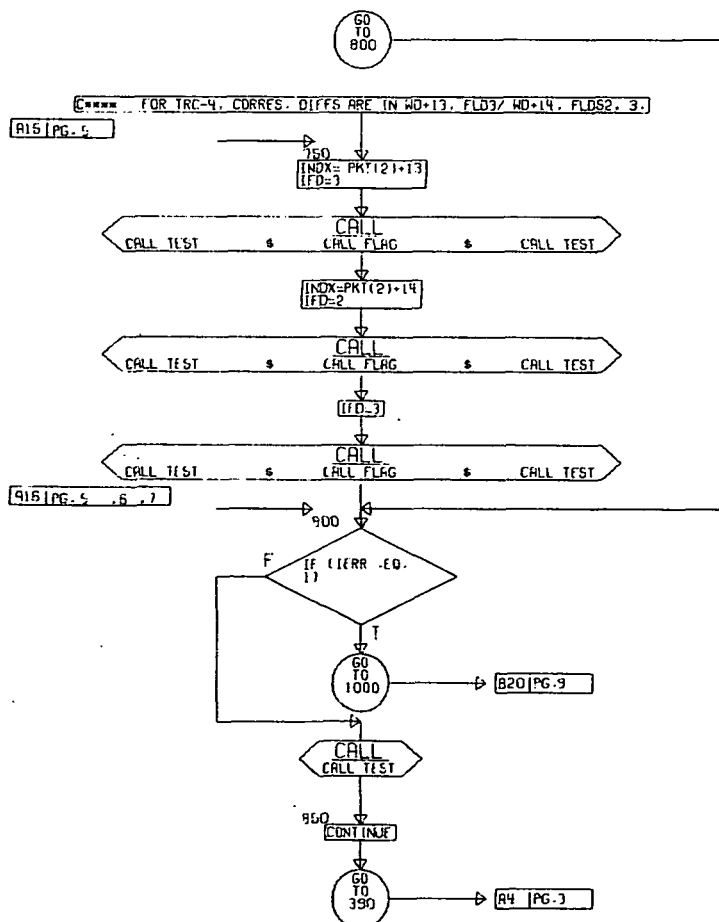
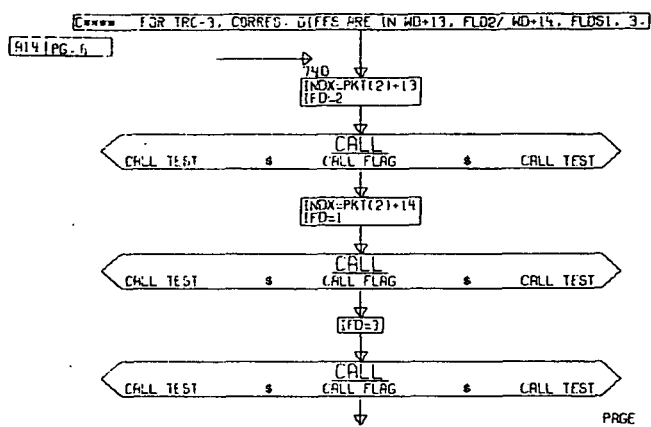
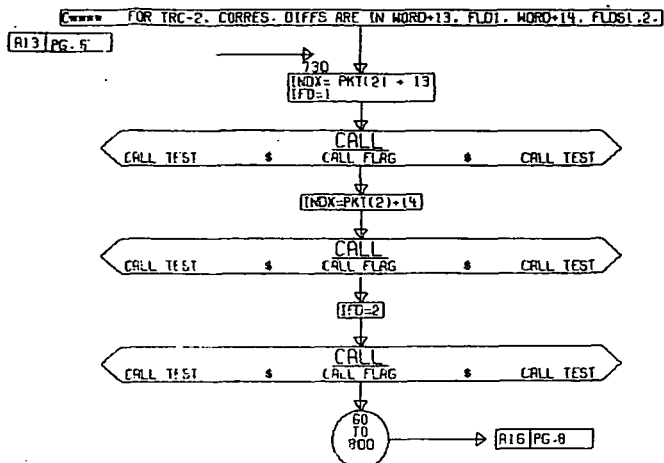
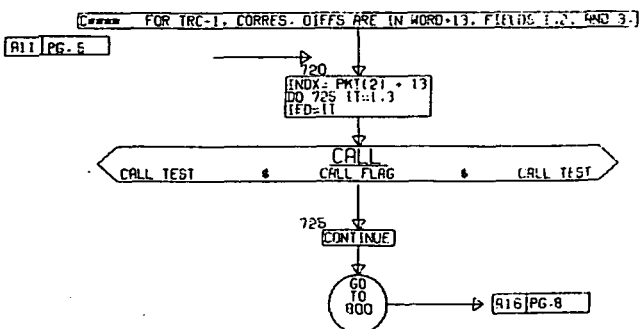
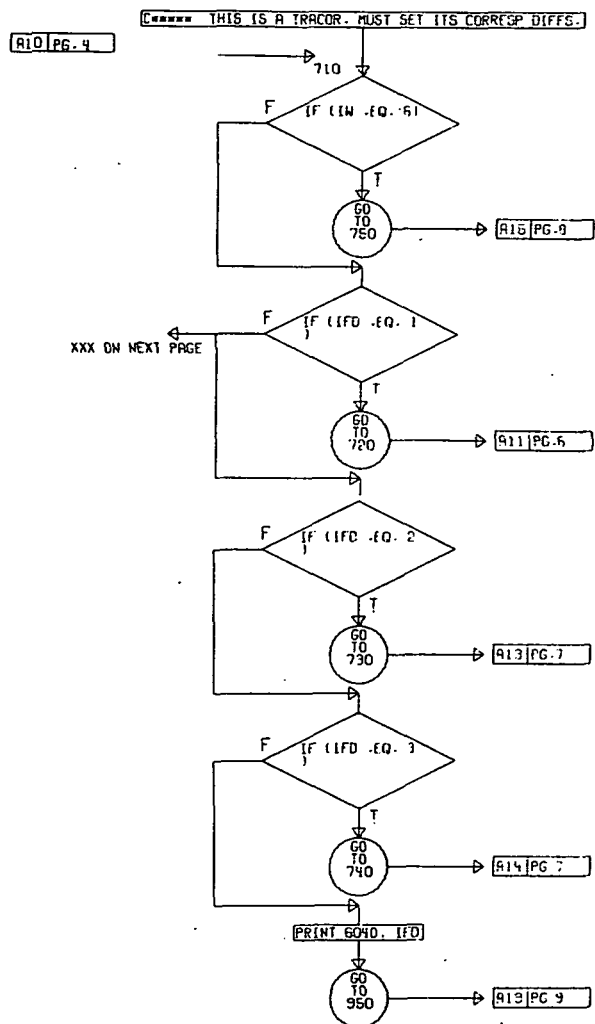
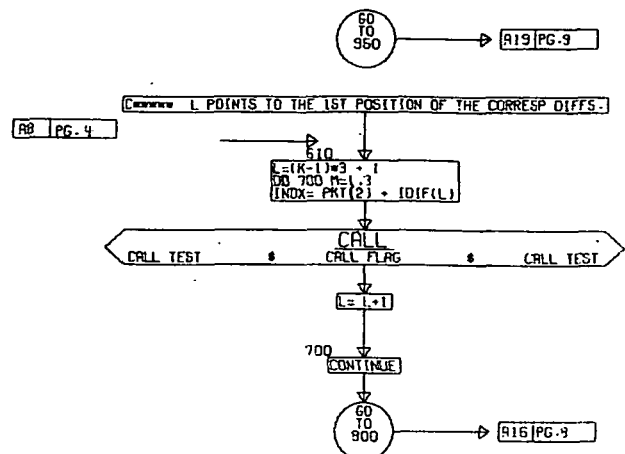
A10 PG-5

F IF (IW .EQ. K)

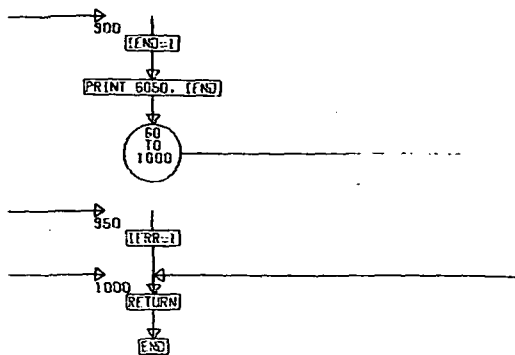
GO
 TO
 610

A8 PG-5

600
 CONTINUE
 PRINT 6030, IW



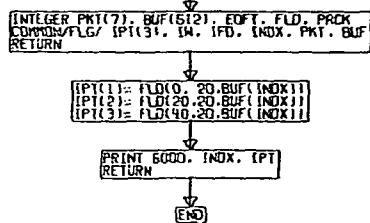
R18 PG. 3



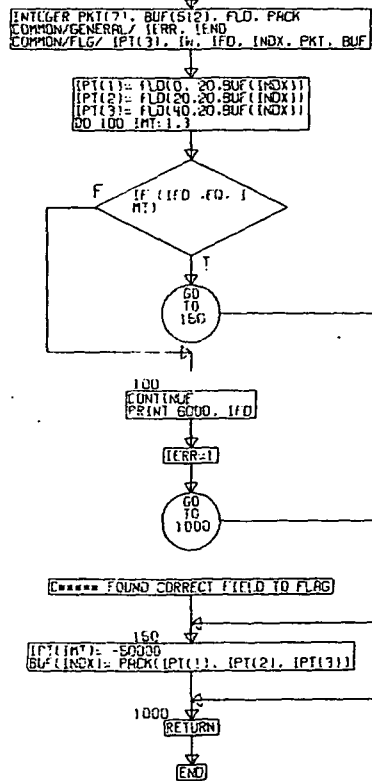
R19 PG. 1, 3, 5, 6

R20 PG. 3, 8

SUBROUTINE TEST



SUBROUTINE FLAG



SUBROUTINE GETCRD(STAPE,ISTUP)

```

COMMON N,(DAY,HR,IMIN,MIN,ITIME(512),XS(512))
DIMENSION STAPE(2),ISTUP(4)
INTEGER PACK,FLO
DIMENSION IX(16),ICMNT(6)
READ 100, STAPE,ISTUP
PRINT 110

```

K=0

K=K+1

READ DATA IN THE FOLLOWING FORMAT
 DAY-HOUR START MIN. END MIN. EDITTING DATA

READ 300, ITIME(K),I,J,X,ICMNT

IF(EOF.5) 400, 301

PACK THE TIME AND THE A/N DATA
 PACK----- THIS FUNCTION PACKS 3 20-BIT VALUES PER WORD
 NP3X16--- THIS FUNCTION PACKS 16 3-BIT VALUES PER WORD

CONTINUE
PRINT 310, ITIME(K),I,J,X,ICMNT

ITIME(K)=PACK(ITIME(K),I,J)

DO 350 I=1,16

IF(I(1).EQ.14)

XXX ON NEXT PAGE

PAGE 2

GO TO 325

XXX FROM LAST PAGE

IX(I)=1

GO TO 350

325 IX(I)=0

350 CONTINUE

IXS(K)=NP3X16(IX)

IF(IXS(K).EQ.0)

GO TO 250

GO TO 200

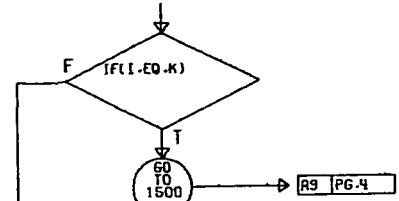
400 K=N

SORT THE DATA IN ASCENDING ORDER BY ITIME

K=N

I=0

I=I+1



A8 PG.4

XXX ON NEXT PAGE

PAGE 4

GO TO 1100

XXX FROM LAST PAGE

```

ITIME(J)=ITIME(J-1)
ITIME(J-1)=I
I=IXS(J)
IXS(J)=XS(J-1)
XS(J-1)=I
J=J-1

```

GO TO 1400

A9 PG.3

CONTINUE
PRINT 1560

```

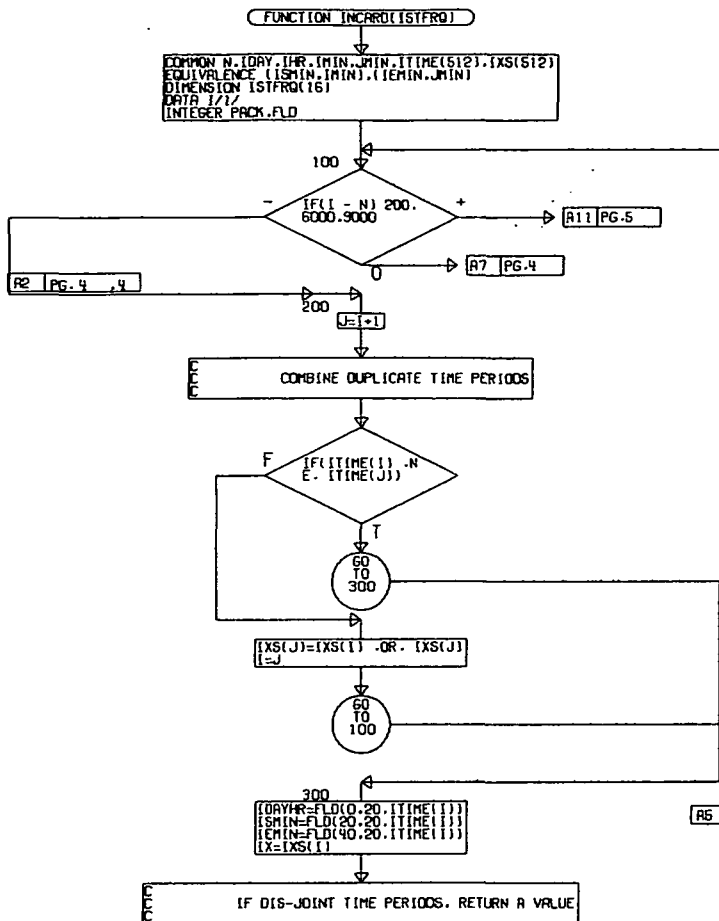
DO 1600 I=1,N
DAYHR=FLO(0.20,ITIME(I))
MIN=FLO(0.40,ITIME(I))
IX=FLO(0.48,IXS(I))

```

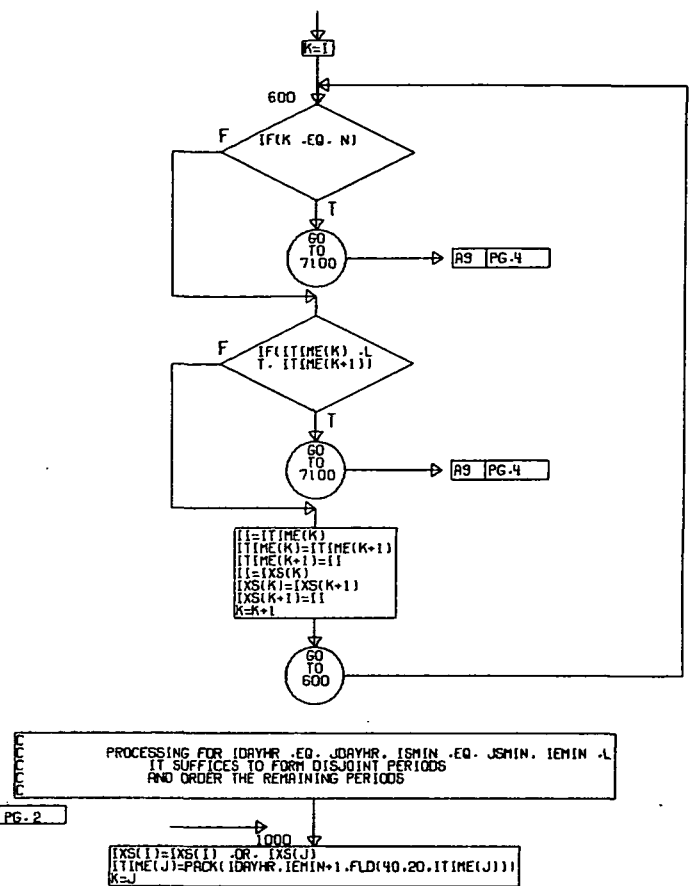
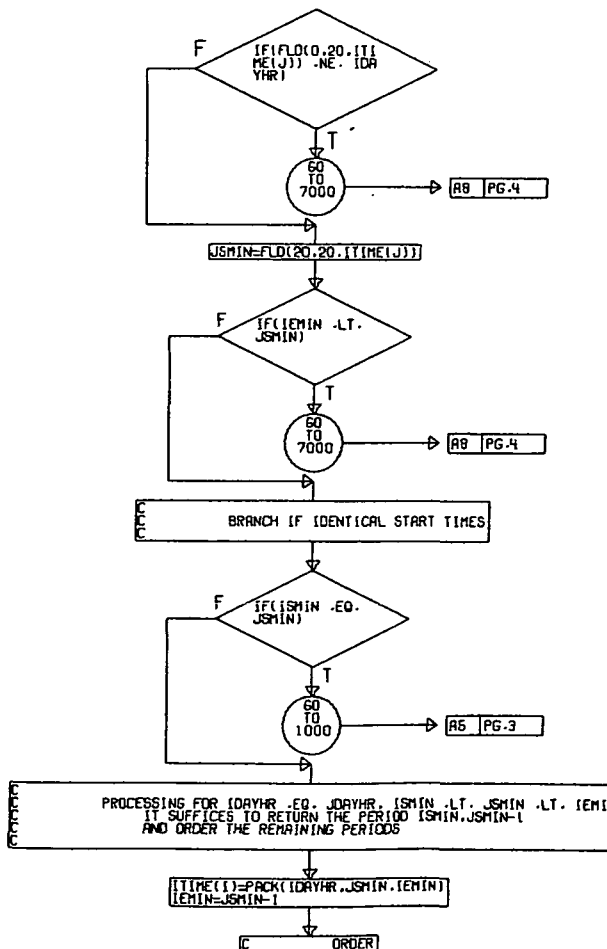
PRINT 1650, DAYHR,IMIN,MIN,IX

RETURN

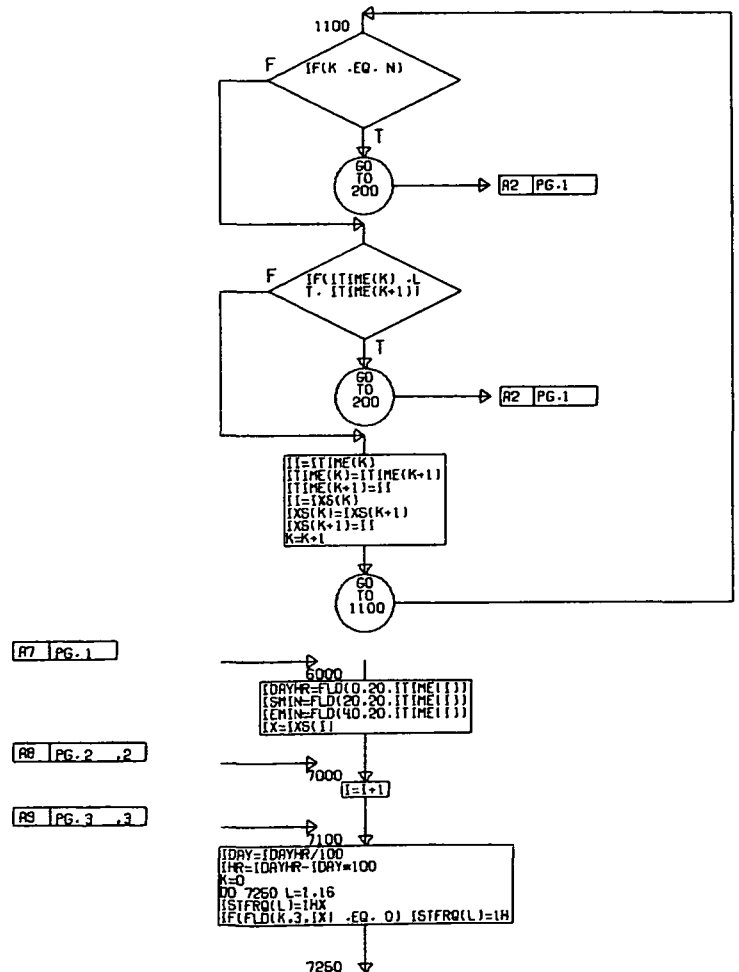
END



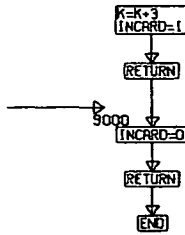
PAGE 2



PAGE 4

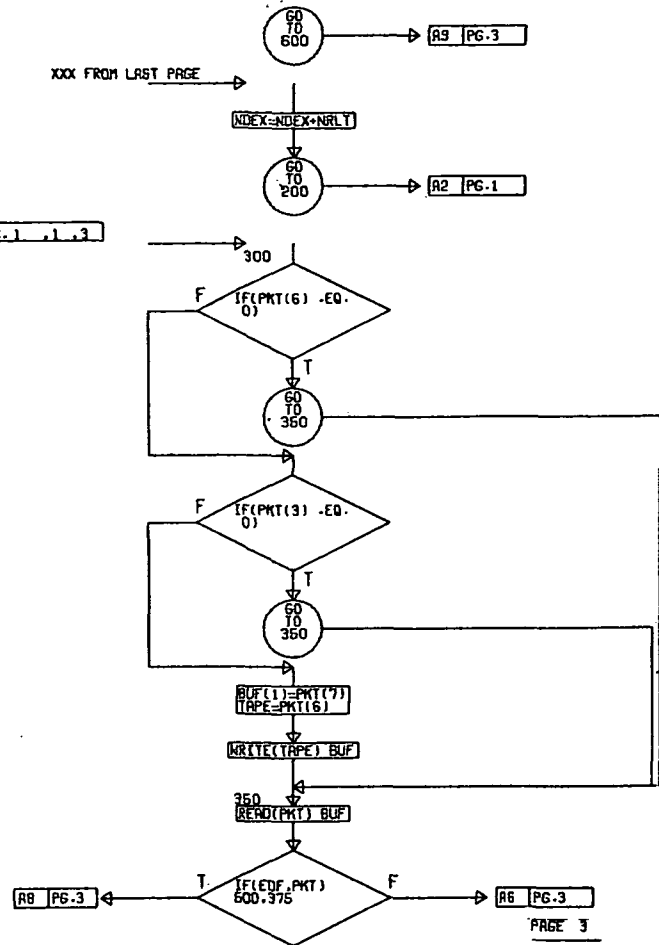


A11 PG. 1



XXX FROM LAST PAGE

A4 PG. 1, 1, 3



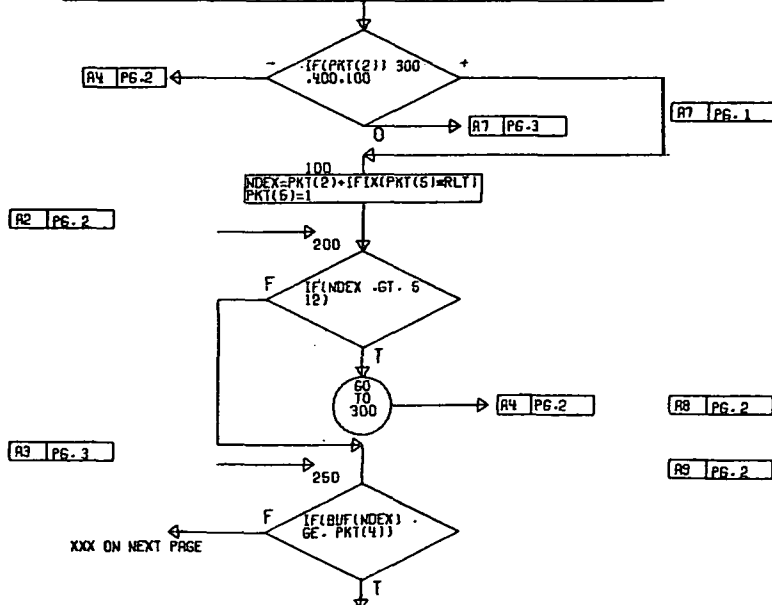
PAGE 1

PAGE 3

INTEGER FUNCTION EOPT(PKT, BUF)
 INTEGER PKT(7), BUF(512), TIME, TAPE
 DATA LOOP/0/, NFMA/3/, NMFB/512/, NRLT/15/, RL/15/

A5 PG. 2

PKT (1) INPUT TAPE NUMBER
 (2) STATUS INPUT:
 0 BEGIN SEARCH W/ BLOCK READ-SEARCH
 1 INPUT TAPE IS ALREADY SETTING ON EOF
 2 BEGIN SEARCH W/ RECORD READ-SEARCH
 3 INVALID (WILL NOT HAPPEN)
 4 EOF DETECTED ON INPUT TAPE
 5 POINTER TO FIRST WORD OF THE NEXT LOGICAL RECORD W/ TIME OF SEARCH-TIME
 N.B. THE FUNCTION VALUE ON RETURN IS THE SAME AS THE ST
 (3) READ BLOCK COUNT
 (4) SEARCH TIME IN SECONDS SINCE THE BEGINNING OF THE YEAR
 (5) RE-READ KEY: 0 BEGIN SEARCH W/ LAST LOGICAL RECORD TO
 1 SKIP LOGICAL RECORDS OR TO NEXT PHYSICAL RECORD (WHICHEVER IS LESS) TO BEGIN SEARCH (FROM LAST LOGICAL RECORD FOUND)
 N.B. THIS MAY BE OVERRIDDEN BY THE INPUT STATUS
 (6) OUTPUT TAPE NUMBER: IF NOT POSITIVE, NO OUTPUT IS DONE
 (7) OUTPUT HEADER REPLACEMENT: IF OUTPUT IS DONE, THE HEADER WORD OF EACH OUTPUT BLOCK IS SET TO THIS VALUE

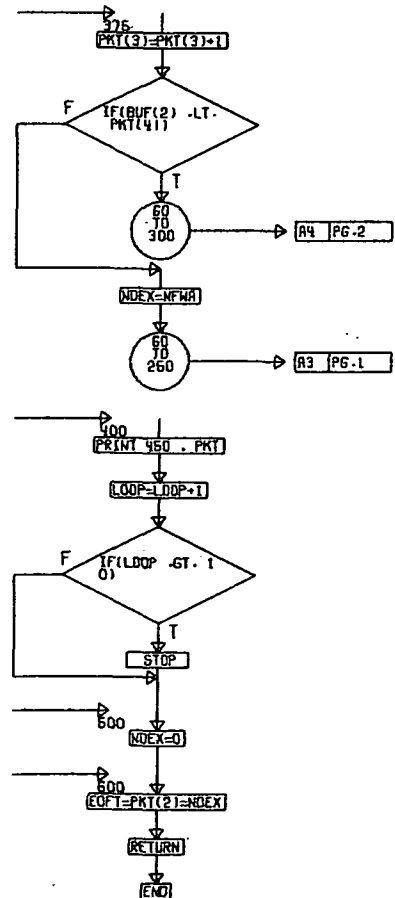


A2 PG. 2

A3 PG. 3

A8 PG. 2

A9 PG. 2



PROGRAM						FORTRAN STATEMENT							PUNCHING HALL CHAINS								CARD PUNCH				PAGE OF				CADD ELECTRO NUMBER																																																					
PROGRAMMER						DATE																																																																												
STATEMENT NUMBER	CARD NO.	INSTR.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68															

Fig. F-2. Sample data set for edit program.

APPENDIX G

SPECIAL SKYWAVE CORRECTION

Currently the OMEGA skywave corrections are calculated for publication by the Hydrographic Center of the Defense Mapping Agency. Upon special written request by RTI the Center has agreed to supply a special set of these corrections to be used in the analysis of data collected during the NASA conducted experiments.

Receiver sites are surveyed and all latitude and longitude values are correct to within approximately $\pm 2\text{m}$. Most of the sites are survey markers placed by either U.S. Coast and Geodetic Survey or respective State survey teams and the markers provide latitude and longitude to the nearest ten-thousandth of a second. Skywave corrections have been requested for each receiver site for the period of time during which data are actually collected. Additionally corrections have been received for one full year for the Langley Research Center site at Hampton, Virginia. Corrections are provided in groups as the times and locations are specified to the Hydrographic Center.

The corrections are unique in that they are calculated for each half hour during each day for the duration of each approximately 3-5 day collection period for each OMEGA frequency (10.2, 11 1/3, and 13.6 kHz) for four transmitter stations (Norway, Trinidad, Hawaii, and North Dakota). Upon receipt the skywave corrections are cataloged, reorganized and placed on 7-track digital magnetic tape in a BCD format. On each catalog tape one or more files are written. Each file has corrections applicable to one receiver site with a file header record to explain the periods and location of the corrections within that file. A Fortran READ statement with a format of 10 (25A4) is used to obtain the file header information. The data are retrieved using a format of 2(I10, 12I4) to get two half hour sets of corrections indexed by a time which is represented in seconds since the beginning of the year plus 86,400. Figure G-1 illustrates this format.

Using the catalog tapes, skywave corrections are generated on a 10 second sample basis from the half hour values for actual use with the recorded data. These are placed in the packed binary format compatible with the recorded data (Figure E-2 in Appendix E). To get 10 second sample values

FILE HEADER RECORD		TIME/DATA RECORD		TIME/DATA RECORD	
FILE HEADER	10 CHARACTER	12 SKYWAVE CORRECTION VALUES	10 CHARACTER	12 SKYWAVE CORRECTION VALUES	10 CHARACTER
E	TIME	NORWAY 10.2, 13.6, 11 1/3	TIME	12I4	TIME
O	CODE	TRINIDAD 10.2, 13.6, 11 1/3	CODE		CODE
F	EACH RECORD	HAWAII 10.2, 13.6, 11 1/3			
M	IS FORMAT	N. DAKOTA 10.2, 13.6, 11 1/3	110		110
A	25A4				
R					
K	BCD WORDS	12I4			

Fig. G-1. 7-Track BCD digital tape format for half hour skywave corrections.

from the half hour values for a given receiver site, a given OMEGA frequency, and a given transmitter, linear interpolation between each consecutive pair of half hour values is used.

To illustrate the procedure let $SWC_A(t_i)$ be the correction, at say 10.2 kHz, for the phase of signal A at a receiver site, and $SWC_B(t_i)$ be the corresponding correction for transmitter B at a half hour time t_i . At time $t_i + 180$, 30 minutes later, let $SWC_A(t_i + 180)$ and $SWC_B(t_i + 180)$ be the corresponding corrections for these two transmissions. Note i indexes ten second values with 180 ten second periods in 30 minutes. Then ten second correction values for A and B are calculated according to

$$SWC_A(t_j) = \frac{SWC_A(t_i + 180) - SWC_A(t_i)}{180} (j - i) + SWC_A(t_i)$$

where $j = i, i + 1, i + 2, \dots, i + 179$ and

$$SWC_B(t_j) = \frac{SWC_B(t_i + 180) - SWC_B(t_i)}{180} (j - i) + SWC_B(t_i) .$$

This provides a set of 180 ten second values to fill the half hour starting at time t_i and ending ten seconds prior to time $t_i + 180$. This procedure is repeated to provide a correction value for each data point in a given data period. For an LOP correction the values for each transmission are formed in the usual manner as

$$SWC_{A-B}(t_j) = SWC_A(t_j) - SWC_B(t_j) .$$

The skywave corrections are merged with the data by adding the appropriate correction to each data word in a data record using a MERGE routine developed at NASA Langley. Ten second clock times at each data record are matched to the nearest five seconds with the clock times associated with the record of corrections.

Figure G-2 provides a FORTRAN listing of the program delivered to NASA at Langley to generate skywave correction values at ten second intervals in the packed binary format using a catalog tape of half hour values which are made at RTI. Input data and format of these data are provided in Table G-1.

Table G-1. Input Data for Packed Skywave Corrections Program (PKSWC)

Input Tape	7-Track BCD Tape of Half Hour SWC Values for Desired Time Period.			
Input Data Cards				
CARD 1	COL 1-40	Start Time:	Day	I5
			Hour	I5
			Minute	I5
			Second	I5
		Stop Time:	Day	I5
			Hour	I5
			Minute	I5
			Second	I5
	COL 41-45	Tracor Receiver Frequency		F5.0
	COL 46-55	Header Flag: Print Input Header		
		Record if Set = 1		I5
		Detailed Printout if Set = 1		I5
CARD 2	COL 1-15	Receiver No.	15	
		Output Tape No.	15	
		Year	15	

The program (PKSWC) should request 226 seconds, 50,000 words of core storage, and 7,800 O/S calls when run on the CDC-6600 system.

Fig. G-2. Program to create 10 sec skywave corrections
from special corrections received from
Defense Mapping Agency.

```

PROGRAM PKSWC(TAPE11,TAPE10,INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C***** PROGRAM-- PACK-SWC-- A. MURRAY
C      THIS PROGRAM IS DESIGNED TO CREATE A PACKED TAPE OF SWC-VALUES
C      FOR ANY GIVEN TIME-PERIOD.
C*****
      DIMENSION IBEG(4), JEND(4)
      DIMENSION IDATA(26), XDAT1(16), XDAT2(16),
      * SWC(16), SWCDIF(24), SVAL(40), IOUT(512)
      COMMON/MAIN/ IEND,IERR,ISECS,JSECS,TRCFQ,IHDG,KOUT,ISECHH,
      * ITIM1, ITIM2, XDAT1, XDAT2, IPT, IDATA, IT,
      * SWC, SWCDIF, JTIM,
      * IFST, IRCVR, ITAPE, IYR, IOUT, ITAPN, ITAPO, IHEND
      DATA ISECS/0/, JSECS/0/, TRCFQ/C./, IHDG/0/, KOUT/0/,
      * ITIM1/0/, ITIM2/0/, XDAT1/16*0./, XDAT2/16*0./, IDATA/26*0/,
      * SWC/16*0./, SWCDIF/24*0./, JTIM/0/,
      * IFST/0/, IOUT/512*0/, ITAPN/10/, ITAPO/11/, IHEND/4H9999/
      EQUIVALENCE (SWC(1),SVAL(1))
C***** INITIALIZE VARIABLES.
      IEND=0
      IERR=0
      ISECHH=1800
      ISECD=86400
      ISECH=3600
      ISECM=60
      IFST=0
      REWIND ITAPN
C***** READ INPUT DATA.
      IBEG(4)-- START TIME IN DAY-HR-MIN-SECS
      JEND(4)-- END TIME IN D-H-M-S
      TRCFQ-- FREQ TO USE FOR TRACOR-CHANNELS
      IHDG-- FLAG=1 SAYS PRINT OUT HEADER-RECS ON TAPE
      IOUT--FLAG=1 SAYS GIVE DETAILED PRINT-CUT
C*****
      READ 5000, IBEG, JEND, TRCFQ, IHDG, KOUT
      5000 FORMAT (8I5,F5.0,2I5)
      ISECS= IBEG(1)*ISECD + IBEG(2)*ISECH + IBEG(3)*ISECM + IBEG(4)
      JSECS= JEND(1)*ISECD + JEND(2)*ISECH + JEND(3)*ISECM + JEND(4)
      PRINT 5100, IBEG, JEND, ISECS, JSECS
      5100 FORMAT (1H-,5X, 29HTIME OF RUN (DAY-HR-MIN-SEC)=, 4I5, 3H TO, 4I5,
      * //, 5X, 8HIN SECS=, I10, 3H TO, I10)
      READ 5000, IRCVR, ITAPE, IYR
C***** CALL SUBROUTINES.

      CALL GETSWC
      IF (IERR) 200,50,200
      50 CALL COMPUT
      200 REWIND ITAPN
      STOP
      END

```

```

SUBROUTINE GETSWC
  DIMENSION TRCMT(3), IHEAD(25)
  DIMENSION IDATA(26), XDAT1(16), XDAT2(16),
  * SWC(16), SWCDIF(24), SVAL(40), IOUT(512)
  COMMON/MAIN/ IEND,IFRR,ISECS,JSECS,TRCFQ,IHDG,KOUT,ISECHH,
  * ITIM1, ITIM2, XDAT1, XDAT2, IPT, IDATA, IT,
  * SWC, SWCDIF, JTIM,
  * IFST, IRCVR, ITAPE, IYR, IOUT, ITAPN, ITAPO, IHEND
  EQUIVALENCE (SWC(1),SVAL(1))
C***** THIS SUBRTN SEARCHES THE SWC-MASTER-FILE UNTIL IT LOCATES THE
C      HALF-HR REC THAT WOULD INCLUDE THE START-TIME. TAPE IS ORDERED
C      CN CONSEC. HALF-HRS WITH VALUES FOR THE 12 FREQ-STATS
C*****
C***** INITIALIZE VARIABLES.
      TRCMT(1)=10.2
      TRCMT(2)=13.6
      TRCMT(3)=11.3
      IPT=-12
      READ INPUT TAPE ITAPN, 5000, IOUT
      IF (EOF,10) 10,20
20    CONTINUE
      STOP 001
10    CONTINUE
C***** DETERMINE FREQ TO USE FOR TRACOR.
      DO 100 IT=1,3
      IF (TRCFQ - TRCMT(IT)) 100,130,100
100  CONTINUE
C      NO MATCH. USE 10.2 DEFAULT OPTION.
      IT=1
CTEMP  READ HEADER BLK. AT LRC, (.EQ.) WILL REPLACE (.XOR.)
130  DO 190 IH=1,10
      READ INPUT TAPE ITAPN, 5000, IHEAD
5000  FORMAT (25A4)
      IF (IHDG) 150,170,150
150  PRINT 5100, IHEAD
5100  FORMAT (1H0, 10X, 25A4)
170  IF (IHEAD(1) .EQ. IHEND) GO TO 200
190  CONTINUE
      PRINT 5200
5200  FORMAT (1H0, 35HND 9999-FLAG FOUND AT END OF HEADER)
C***** READ TAPE UNTIL TIME(SECS) IS WITHIN HALF-HR. OF START-TIME.
200  ISEK=1
230  IPT=MOD(IPT+13,26)
      IF (IPT-1) 250,250,270
250  READ INPUT TAPE ITAPN, 5500, IDATA
5500  FORMAT (2(110, 1214))
270  GO TO (290,350), ISEK
290  IDIF= ISECS-IDATA(IPT)
      IF (IDIF - ISECHH) 300,230,230
C***** THE 1ST HALF-HR HAS BEEN FOUND. CALL GETDAT.
300  CALL GETDAT (IDATA, XDAT1, ITIM1, IPT, IT)
      ISEK=2
CTEMP  DIAG. PRINT.
      IF (KOUT) 310,230,310
310  PRINT 6005, IDATA
6005  FORMAT (1H0,5X, 9HUSE REC--,/, 2X, 2(110,1214),/)
      PRINT 6000, ISECS, ITIM1, XDAT1
6000  FORMAT (1H0,5X, 18HSTART-TIME (SECS)=, 110,13H 1ST HALF-HR=, 110,
  * //, 6X, 16F7.2)
      GO TO 230
C***** THE 2ND HALF-HR FOUND.
350  CALL GETDAT (IDATA,XDAT2, ITIM2, IPT, IT)
CTEMP  DIAG PRINT.
      IF (KOUT) 370,390,370
370  PRINT 6100, ITIM2, XDAT2
6100  FORMAT (1H0,5X, 12H2ND HALF-HR=, 110,/, 6X, 16F7.2)
390  RETURN
      END

```

```

SUBROUTINE COMPUT
  DIMENSION YVALU(16)
  DIMENSION IDATA(26), XDAT1(16), XDAT2(16),
  * SWC(16), SWCDIF(24), SVAL(40), IQOUT(512)
  COMMON/MAIN/ IEND, IERR, ISECS, JSECS, TRCFQ, IHOG, KOUT, ISECHH,
  * ITIM1, ITIM2, XDAT1, XDAT2, IPT, IDATA, IT,
  * SWC, SWCDIF, JTIM,
  * IFST, TRCVR, ITAPE, IYR, IQOUT, ITAPN, ITAPO, IHEND
  EQUIVALENCE (SWC(1), SVAL(1))
C***** THIS SUBRTN COMPUTES INTERPOLATED-SWC VALUES FOR EACH 10-SECS
C      BETWEEN A HALF-HR PERIOD.
C      INTPLT  XDAT1+ ( (XDAT2-XDAT1) / (ITIM2-ITIM1) ) * (JTIM-ITIM1)
C*****
      XTPLT(SWC1, SVALU, TMDIF) = SWC1 + (SVALU * TMDIF)
C***** INITIALIZE VARIABLES.
      ITVAL = 10
      XTVAL = ITVAL
      JTIM = ISECS
C***** COMPUTE CONSTANTS FOR INTERPLTN.
      100 TME = ITIM2 - ITIM1
      IF ((JSECS - JTIM) - ISECHH) 102, 103, 103
      102 IF ((ITIM2 - JSECS) 103, 104, 104
      103 JMAX = (FLOAT(ITIM2 - JTIM) / XTVAL) + 1.
      GO TO 106
      104 JMAX = (FLOAT(JSECS - JTIM) / XTVAL) + 1.
      106 IF (KOUT) 110, 130, 110
      110 PRINT 6000, JMAX
      6000 FORMAT (1H0, 5X, I4, 22H INTERPOLATIONS NEEDED)
      130 DO 150 N1 = 1, 16
      YVALU(N1) = (XDAT2(N1) - XDAT1(N1)) / TME
      150 CONTINUE
C
      DO 300 JCNT = 1, JMAX
      TMDIF = JTIM - ITIM1
      DO 200 N2 = 1, 12
      SWC(N2) = XTPLT(XDAT1(N2), YVALU(N2), TMDIF)
      200 CONTINUE
      JTRC = IT
      DO 250 N3 = 13, 16
      SWC(N3) = SWC(JTRC)
      JTRC = JTRC + 3
      250 CONTINUE

CTEMP  DIAG. PRINTS.
      IF (KOUT) 270, 290, 270
      270 PRINT 6100, JCNT
      6100 FORMAT (1H0, 6HINTPLT, I4, 1H=)
      PRINT 6200, SWC
      6200 FORMAT (1H0, 8F12.5)
      290 CALL CMPDIF
      CALL PRTREC
      JTIM = JTIM + ITVAL
      300 CONTINUE
CTEMP
      IF (KOUT) 310, 330, 310
      310 PRINT 6205, JTIM
      6205 FORMAT (1H0, 20HAT END OF LOOP JTIM=, I10)
C***** GO TO NEXT HALF-HR IF LESS THAN JSECS (ENDTM).
      330 IF ((ITIM2 - JSECS) 400, 1000, 1000
      400 ITIM1 = ITIM2
      DO 450 IMV = 1, 16
      XDAT1(IMV) = XDAT2(IMV)
      450 CONTINUE
      IPT = MOD(IPT + 13, 26)
      IF (IPT - 1) 470, 470, 500
      470 READ INPUT TAPE ITAPN, 5500, IDATA

```



```

5500 FORMAT (2(I10, 12I4))
500 CALL GETDAT (IDATA, XDAT2, ITIM2, IPT, IT)
CTEMP   CIAG PRINT.
        IF (KOUT) 510,100,510
510 PRINT 6305, IDATA
6305 FORMAT (1H0,5X, 9HUSE REC--,/,1X,2(I10,12I4),/)
        PRINT 6300, ITIM1, ITIM2, XDAT1, XDAT2
6300 FORMAT (1H~, 25HNEXT TIME INTERVAL--TIM1=, I10, 5HTIM2=, I10,
* //,5X, 16F7.2,/,5X,16F7.2)
        GO TO 100
1000 IEND=1
        JTIM=JTIM-ITVAL
        CALL PRTRC
        RETURN
        END

```

```

SUBROUTINE GETDAT (IDATA, XDATA, ITIM, IPT, IT)
C***** THIS SUBRIN LOCATES THE LOGICAL RECORD.
C*****
        DIMENSION IDATA(26), XDATA(16), CONST(3)
C***** INITIALIZE VARIABLES.
        CONST(1)=1.
        CONST(2)=1.
        CONST(3)=1.
        JPT=IPT
        ITIM=IDATA(JPT)
        JTRC=IT
        DO 100 IMV=1,12
        IC=MOD(IMV,3)
        IF (IC) 50,30,50
30 IC=3
50 JPT=JPT+1
        XDATA(IMV)= FLOAT(IDATA(JPT)) * CONST(IC)
100 CONTINUE
C***** FIND SWC S FOR TRACOR.
        DO 200 IMV=13,16
        XDATA(IMV)= XDATA(JTRC)
        JTRC=JTRC+3
200 CONTINUE
        RETURN
        END

```

```

SUBROUTINE CMPDIF
  DIMENSION IDATA(26), XDATA1(16), XDATA2(16),
  * SWC(16), SWCDIF(24), SVAL(40), IOUT(512)
  COMMON/MAIN/ IEND, IERR, ISECS, JSECS, TRCFQ, IHOG, KOUT, ISECHH,
  * ITIM1, ITIM2, XDATA1, XDATA2, IPT, IDATA, IT,
  * SWC, SWCDIF, JTIM,
  * IFST, IRCVR, ITAPE, IYR, IOUT, ITAPN, ITAPO, IHEND
  EQUIVALENCE (SWC(1), SVAL(1))
C***** THIS SUBRTN USES THE INTERPOLATED SWC-VALUES TO COMPUTE THE
C      STATION-PAIR SWC-VALUES.
C      FOLLOWING COUNTERS MUST BE INITZ 0 EACH TIME
C      IDIF--COUNTS NO. OF ELEMENTS IN SWCDIF (SWCDIF(1) TO SWCDIF(24))
C      IPRS--SETS LOOP TO MATCH ALL POSS. STATS. WITH 1ST ONE THE SAME
C      ISTRT--LOCATES SINGLE SWC-VAL IN SWC-ARRAY FOR TERM1 OF DIFF
C      JSTRT--LOCATES SWC-VAL IN SWC-ARRAY FOR TERM2 OF DIFF
C      ORDER OF DIFFS-- 1-4/2-5/3-6/ 1-7/2-8/3-9/ 1-10/2-11/3-12
C      4-7/5-8/6-9/ 4-10/5-11/6-12/ 7-10/8-11/9-12/
C      13-14/13-15/13-16/ 14-15/14-16/15-16/
C      INDS. MUST BE PRESET FOR EACH CALL TO THIS SUBRTN.
C*****
  IDIF=1
  IPRS=3
  ISTRT=1
  JSTRT=4
  DO 200 IM=1,3
    DO 100 IP=1,IPRS
      SWCDIF(IDIF)= SWC(ISTRT) - SWC(JSTRT)
      SWCDIF(IDIF+1)= SWC(ISTRT+1) - SWC(JSTRT+1)
      SWCDIF(IDIF+2)= SWC(ISTRT+2) - SWC(JSTRT+2)
      IDIF=IDIF+3
      JSTRT=JSTRT+3
    100 CONTINUE
    IPRS=IPRS-1
    ISTRT=ISTRT+3
    JSTRT=JSTRT+3
  200 CONTINUE
  SWCDIF(19)= SWC(13)-SWC(14)
  SWCDIF(20)= SWC(13)-SWC(15)
  SWCDIF(21)= SWC(13)-SWC(16)
  SWCDIF(22)= SWC(14)-SWC(15)
  SWCDIF(23)= SWC(14)-SWC(16)
  SWCDIF(24)= SWC(15)-SWC(16)
CTEMP
  IF (KOUT) 210,230,210
  210 PRINT 6000, SWCDIF
  6000 FORMAT (1H0,5X, 14H$SWCDIF VALUES=,/, 4(1X,3F12.5,5X,3F12.5,/))
  230 RETURN
  END

```

```

      SUBROUTINE PRTREC
      DIMENSION IPART(3)
      DIMENSION IDATA(26), XDAT1(16), XDAT2(16),
      * SWC(16), SWCDIF(24), SVAL(40), IOUT(512), IFLG(5)
      COMMON/MAIN/ IEND, IERR, ISECS, JSECS, TRCFQ, IHOG, KOUT, ISECHH,
      * ITI 1, ITIM2, XDAT1, XDAT2, IPT, ICATA, IT,
      * SWC, SWCDIF, JTIM,
      * IFST, IRCVR, ITAPE, IYR, ICUT, ITAPN, ITAPO, IHEND
      DATA IFLG/73,0,0,0,0/
      INTEGER PACK, HEADER
      EQUIVALENCE (SWC(1), SVAL(1))
C***** THIS SUBRTN PACKS AND STORES EACH 10-SEC REC. UNTIL 512-BUFR
C      IS FULL. IT THEN WRITES THE THE PACKED RECORD.
C*****
      IF (IFST) 100,50,100
C***** INITIALIZE VARIABLES.
      50 IZERO=0
      II=2
      IREC=C
      IFST=1
C
C*****
C      NEED TO USE LRC-HEADER RTN TO PACK 1ST WORD.
C*****
C      IOUT(1)= HEADER (IRCVR, ITAPE, 0, 0, IFLG)
      IF (KOUT) 70,100,70
      70 PRINT 600J, IRCVR, ITAPE, IYR
      6000 FORMAT (1H-, 5X, 28H IOUT 1--RECV, TAPE-NO, YR=, 3I5)
      100 IF (IEND) 500,150,500
C***** INCREMENT WORD-CNTR (II) AND LOGICAL-REC-CNTR (IREC).
      150 II=II+1
      IREC=IREC+1
      IOUT(II)=JTIM
      IF (KOUT) 170,190,170
      170 PRINT 610C, II, IOUT(II)
      6100 FORMAT (6X, 4H IOUT, 14, 3H= , 11C)
C***** LOOP TO PACK 40 SWC AND SWC-DIFF. VALUES FOR THIS 10-SEC TIME.
      190 JBEG=1
      JEND=15
      DO 300 JJ=1,2
      DO 200 JPK=JBEG, JEND, 3

      II=II+1
C***** ROUND OFF BEFORE CHANGING TO AN INTEGER.
      SVAL(JPK)= SVAL(JPK) + SIGN(.005, SVAL(JPK))
      SVAL(JPK+1)= SVAL(JPK+1) + SIGN(.005, SVAL(JPK+1))
      SVAL(JPK+2)= SVAL(JPK+2) + SIGN(.005, SVAL(JPK+2))
      IPART(1)= SVAL(JPK)*100.
      IPART(2)= SVAL(JPK+1)*100.
      IPART(3)= SVAL(JPK+2)*100.
C
C*****
C      NEED TO USE LRC S PACK RTN TO PACK 3 SWC-VALUES AT A TIME.
C*****
C
      IOUT(II)= PACK(IPART(1), IPART(2), IPART(3))
      IF (KOUT) 195,200,195
      195 PRINT 620J, II, IPART
      6200 FORMAT (6X, 4H IOUT, 14, 3H= , 3I10)
      200 CONTINUE
      IF (JJ-1) 250,250,300
      250 II=II+1
      ITR4= (SVAL(16) + SIGN(.005, SVAL(16))) * 100.

```

```

C
C*****C
C      USE PACK FOR WORD 16 WHICH CONTAINS 2 ZEROES.
C*****C
C
      IOUT(II)= PACK(ITR4, IZERC, IZERO)
      IF (KOUT) 270,290,270
270 PRINT 6200, II, ITR4, IZERO, IZERO
290 JREG=17
      JEND=40
300 CONTINUE
      IF (IREC-34) 600,330,310
C
310 PRINT 5000, IREC
5000 FORMAT (1H0, 32HERR IN RECORD-CNT OF IOUT-ARRAY=, I5)
      GO TO 590
330 IF (II-512) 350,400,350
C
350 PRINT 5100, II
5100 FORMAT (1H0, 30HERR IN WORD-CNT OF IOUT-ARRAY=, I5)
      GO TO 590
C***** STORE FINAL BLK-TM AND WRITE RECORD TO TAPE.

400 IOUT(2)=JTIM
      IREC=0
      II=2
C
C*****C
C      WRITE BINARY TAPE OF INTERPOLATED SWC-VALUES.
C*****C
C
      WRITE (ITAPD) IOUT
      IF (KOUT) 410,600,410
410 PRINT 6300, IOUT(2)
6300 FORMAT (1H0, 25HRECORD COMPLETED AT TIME=, I10)
      GO TO 600
C***** HAVE COMPLETED TIME-PERIOD. MUST PAD IOUT WITH ZEROS.
500 ICCMPL=II+1
      DO 550 KK=ICMPL,512
      IOUT(KK)=0
550 CONTINUE
      GO TO 400
C
590 IERR=1
600 RETURN
      END

```

```
PROGRAM PKSMC(TAPE11,TAPE10,INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
```

```
***** PROGRAM-- PKCH-SMC-- A. MURRAY
THIS PROGRAM IS DESIGNED TO CREATE A PACKED TAPE OF SMC-VALUES
FOR ANY GIVEN TIME-PERIOD.
*****
```

```
      DIMENSION (BEG(4), JEND(4))
```

```
      DIMENSION (DATA(26), XDAT1(16), XDAT2(16),
     1 SMC(16), SMCDF(24), SVAL(40), OUT(612))
```

```
      COMMON/MAIN/ IEND,IERR,ISECS,JSECS,TRCFQ,INDG,KOUT,ISECH,
     1 ITM1,ITM2,XDAT1,XDAT2,IPT,IDATA,IT,
     2 SMC,SMCDF,JTIM,
     3 IFST,IRCVR,ITAPE,IYR,IOUT,ITAPN,ITAPQ,IHEND
```

```
      DATA ISECS/0/, JSECS/0/, TRCFQ/0./, INDG/0/, KOUT/0/,
     1 ITM1/0/, ITM2/0/, XDAT1/16*0./, XDAT2/16*0./, IDATA/26*0/,
     2 SMC/16*0./, SMCDF/24*0./, JTIM/0/,
     3 IFST/0/, IOUT/612*0./, ITAPN/10/, ITAPQ/11/, IHEND/4H9999/
```

```
      EQUIVALENCE (SMC(1),SVAL(1))
```

```
***** INITIALIZE VARIABLES.
```

```
      IEND=0
      IERR=0
      ISECH=1800
      ISECD=86400
      ISECH=3600
      IFST=0
```

```
      REWIND (TAPN)
```

```
***** READ INPUT DATA.
      (BEG(4)-- START TIME IN DAY-HR-MIN-SECS
      JEND(4)-- END TIME IN D-H-M-S
      TRCFQ-- FLAG TO USE FOR TRACOR-CHANNELS
      INDG-- FLAG=1 SAYS PRINT OUT HEADER-RECS ON TAPE
      IOUT--FLAG=1 SAYS GIVE DETAILED PRINT-OUT
*****
```

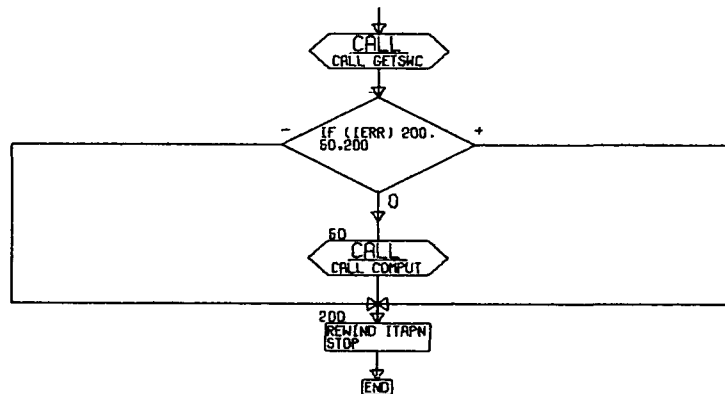
```
      READ 5000, (BEG, JEND, TRCFQ, INDG, KOUT)
```

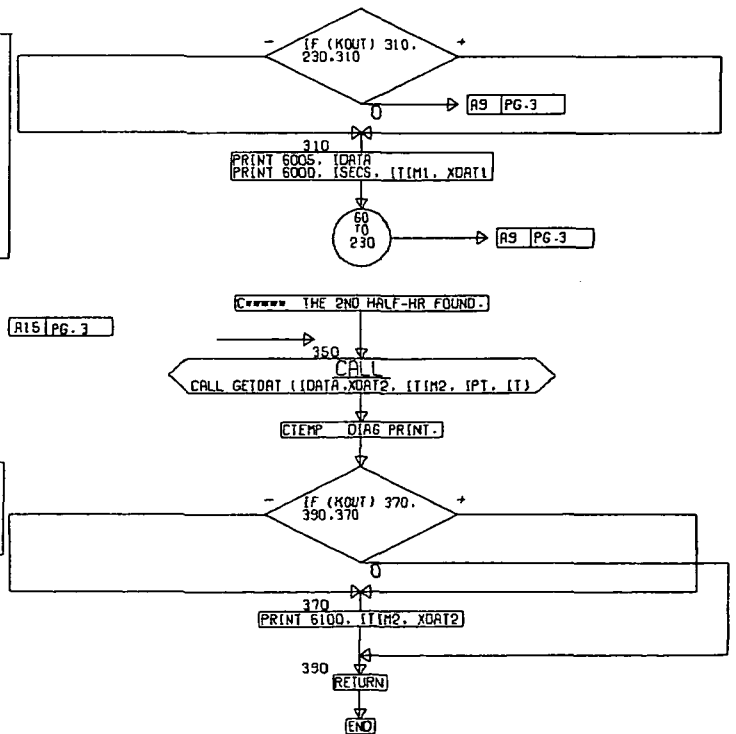
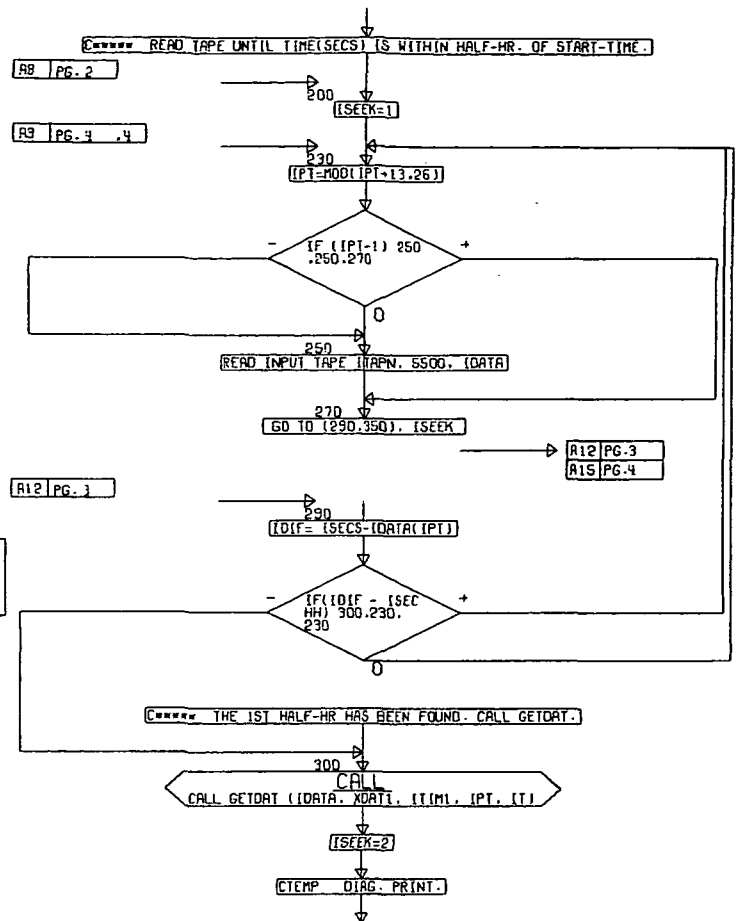
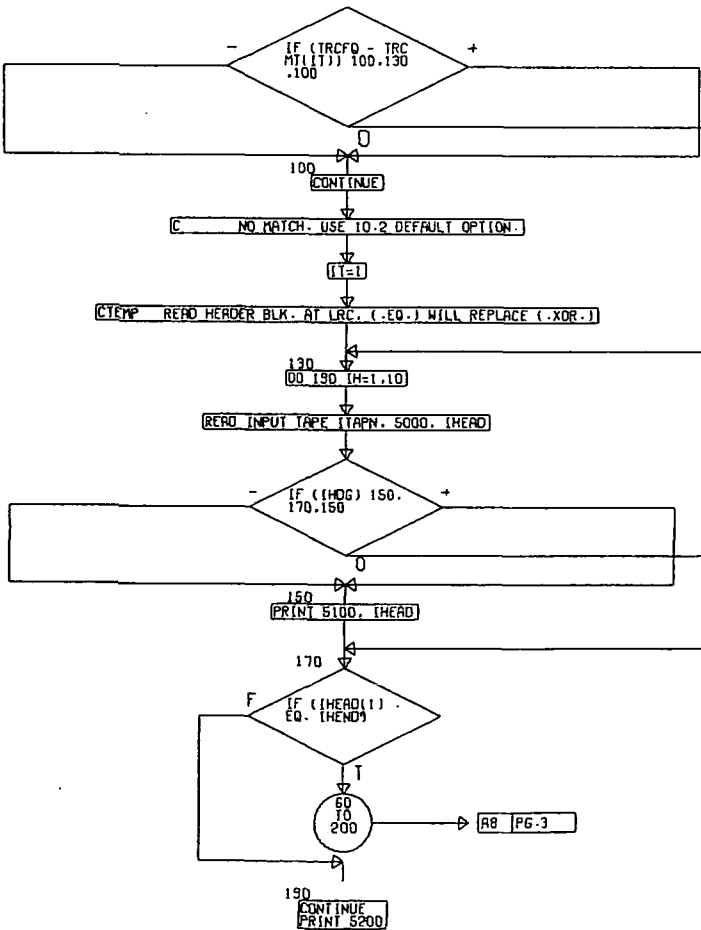
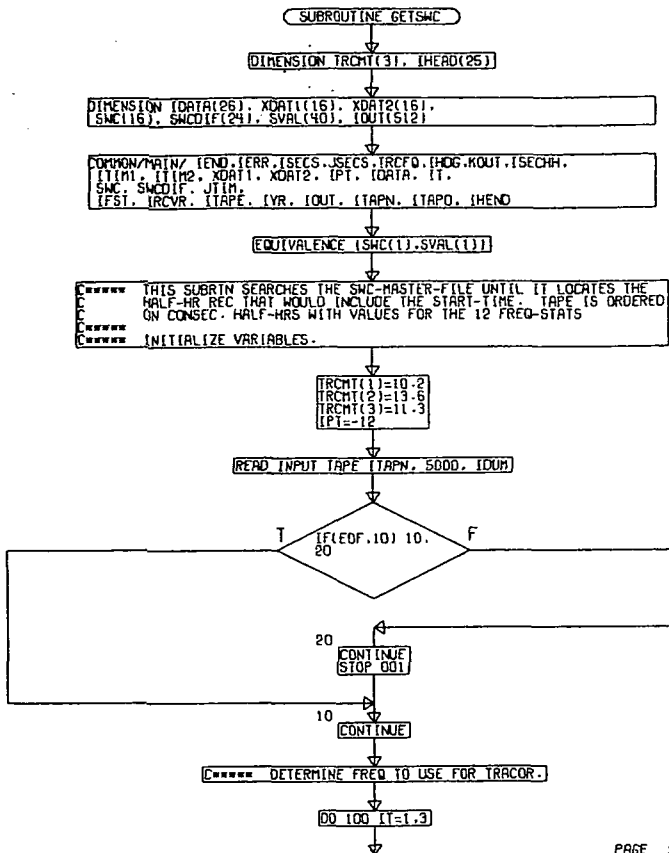
```
      ISECS= (BEG(1)=ISECD + (BEG(2)=ISECH + (BEG(3)=ISECH + (BEG(4)
     1 JSECS= JEND(1)=ISECD + JEND(2)=ISECH + JEND(3)=ISECH + JEND(4)
```

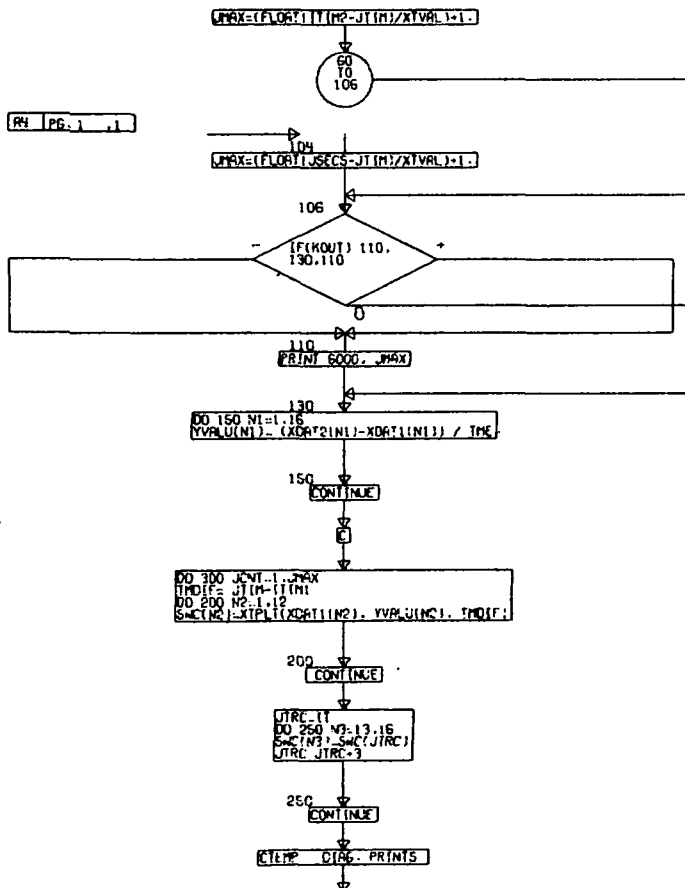
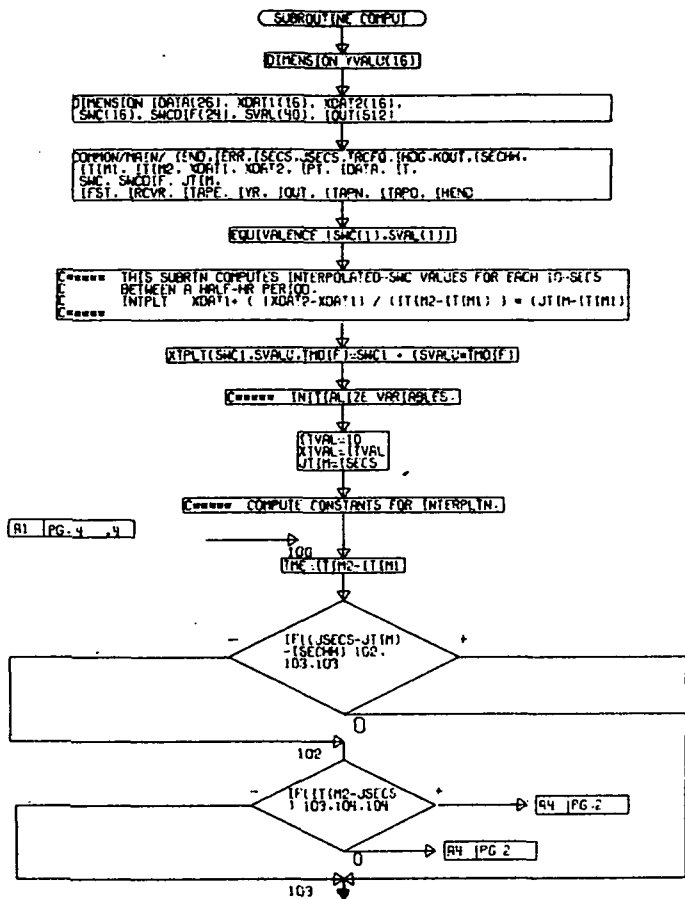
```
      PRINT 5100, (BEG, JEND, ISECS, JSECS
     1 READ 5000, IRCVR, ITAPE, IYR
```

```
***** CALL SUBROUTINES.
```

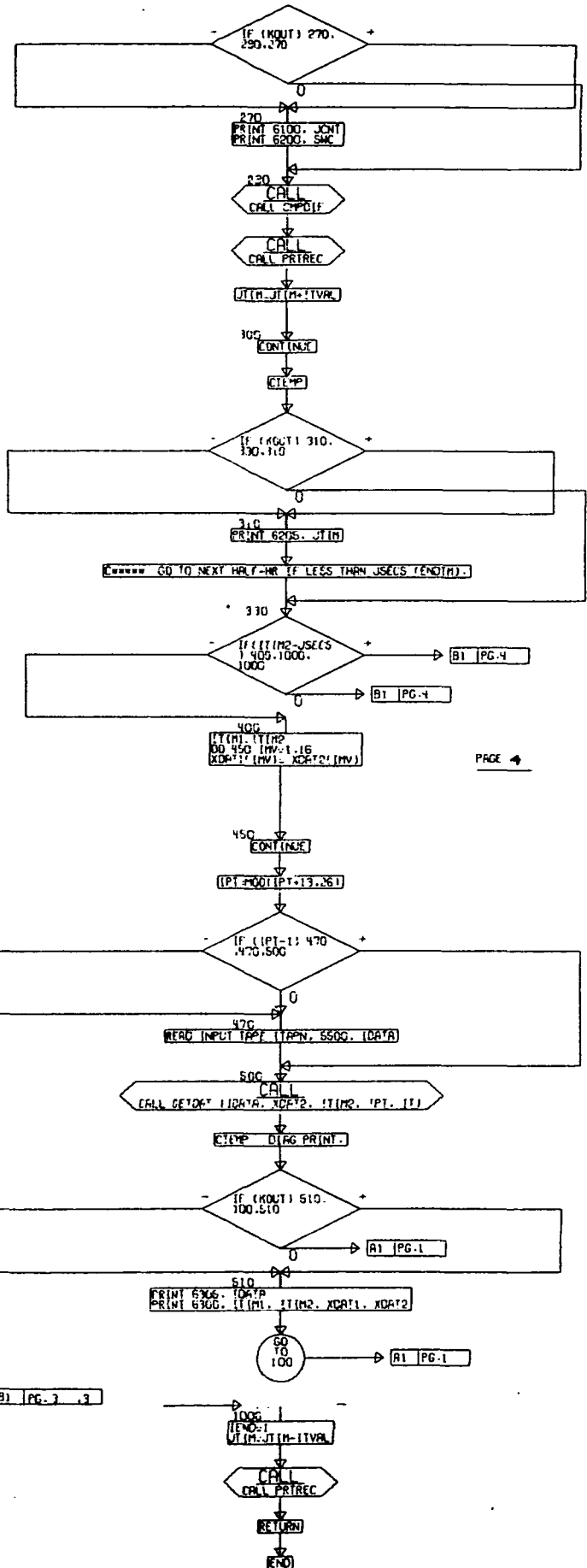
PAGE 2

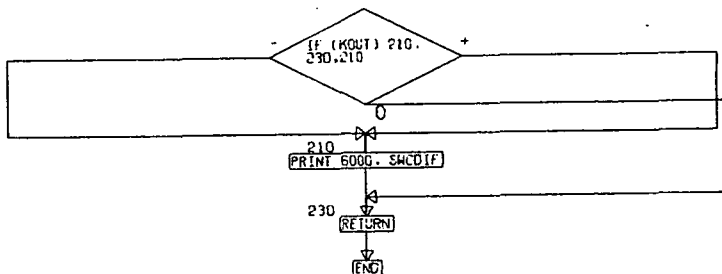
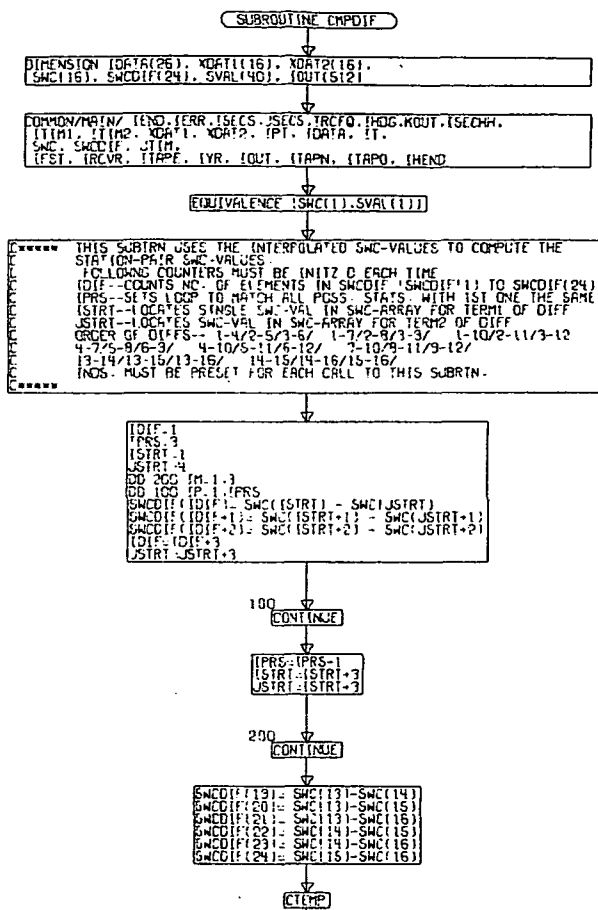
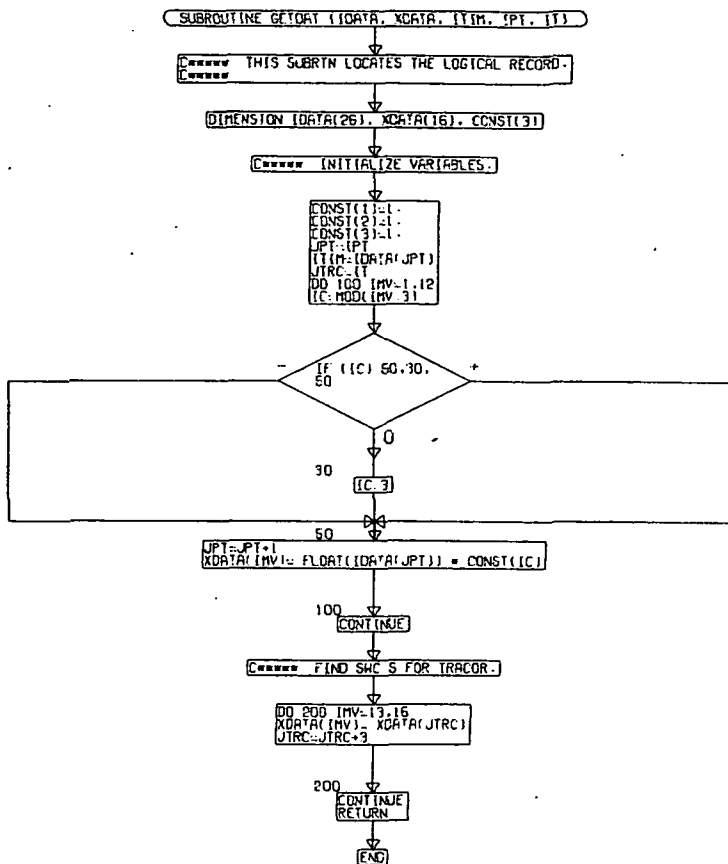


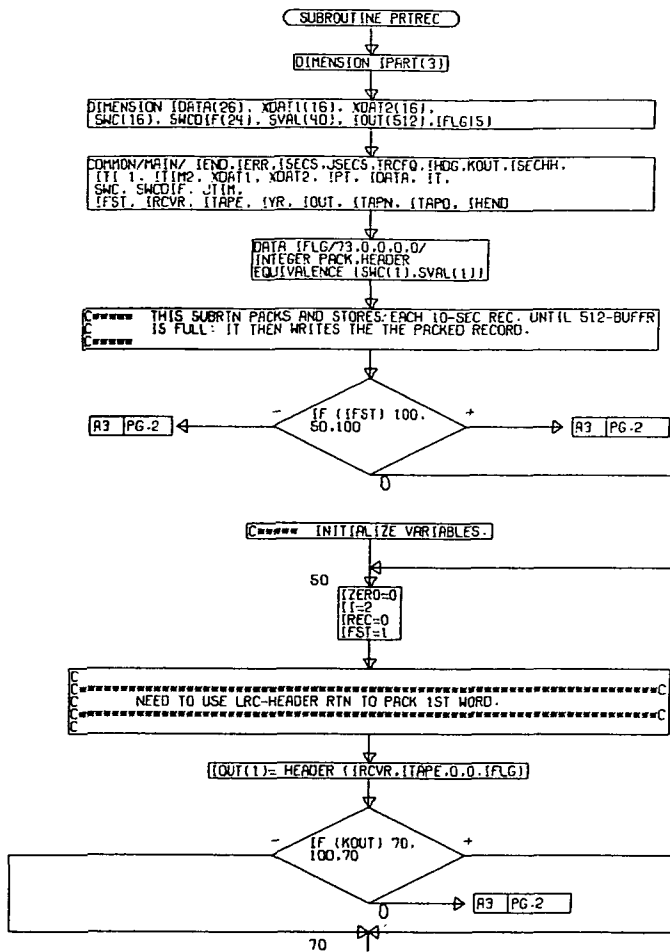




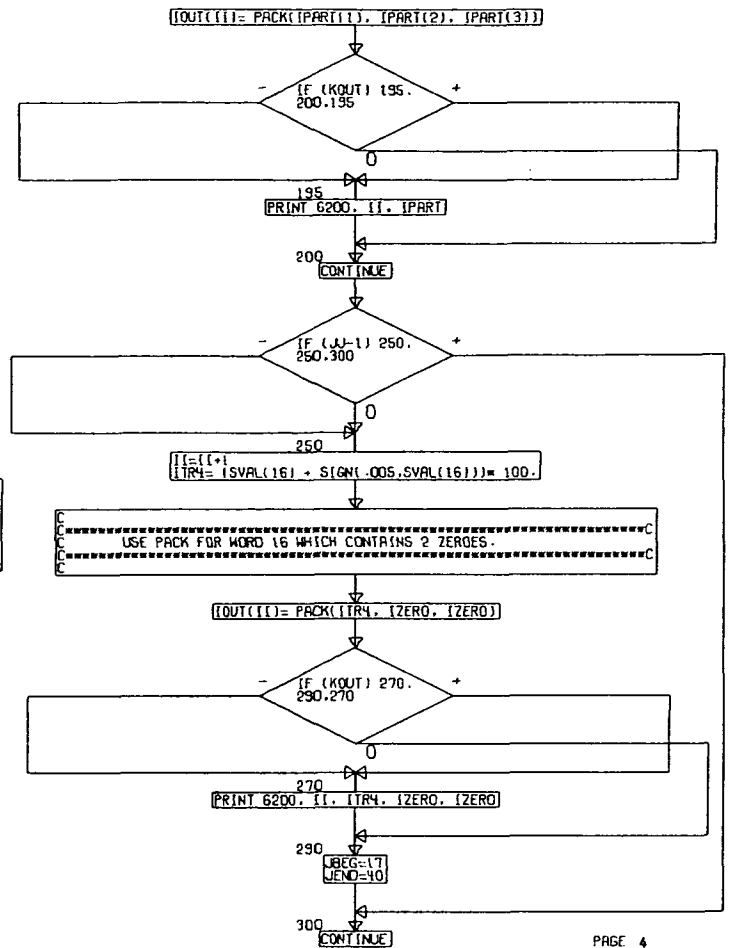
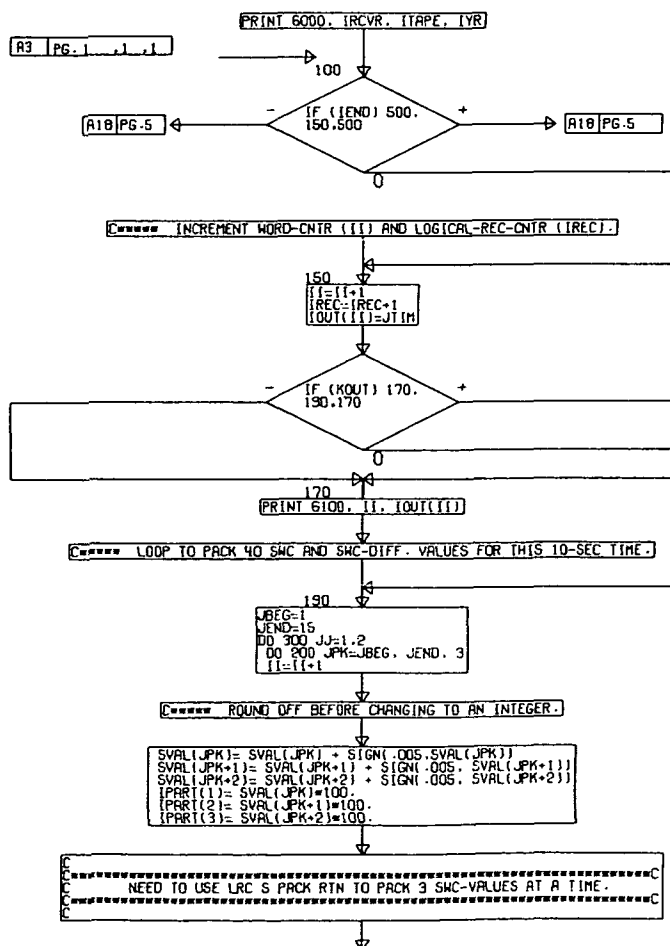
A1 PG. 1 .1



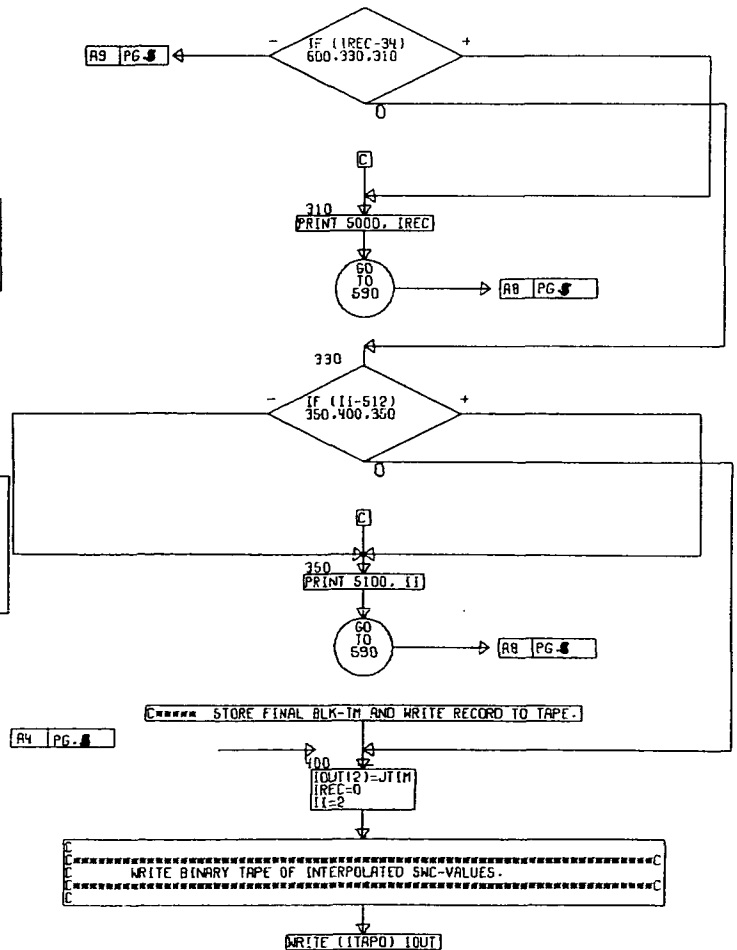


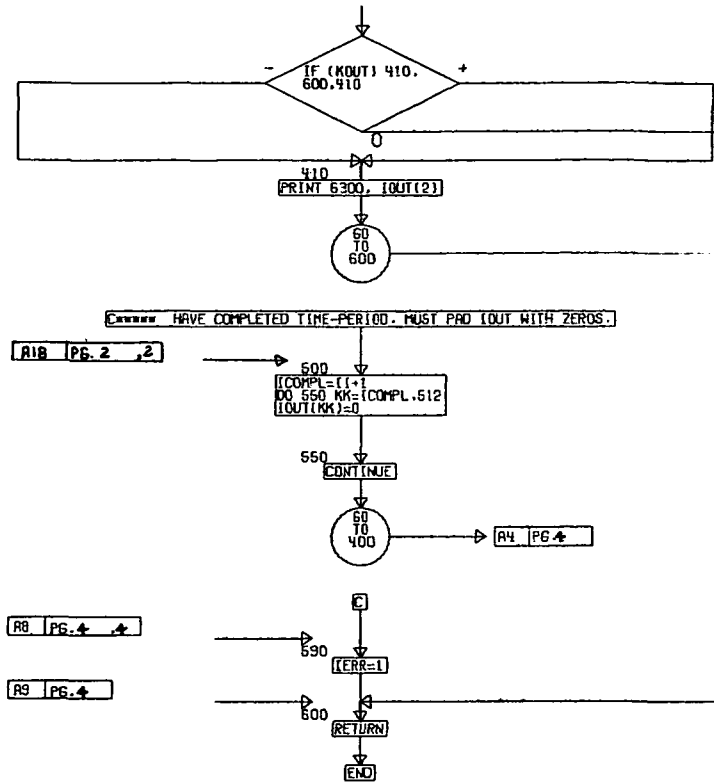


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APPENDIX H

STATISTICAL ANALYSIS OF RECORDED OMEGA DATA

The OMEGA receiver data are recorded on digital tape in 10 second intervals at each receiver complex. The raw data contain relative phase measurement of each transmitter signal from stations A, B, C, and D for all three frequencies as measured by the NASA-built digital phase-locked loop receiver and each transmitter station for the selected frequency on the Tracor receiver. The data are subsequently reformatted and rewritten onto packed binary tapes and edited (Appendix F). Various types of analysis are possible using the packed tapes as input to the statistical analysis program. These include: LOP measurement accuracy analysis, side-by-side receiver (repeatability) analysis, and uncorrected differential OMEGA error analysis and skywave-corrected differential OMEGA error analysis.

The Analysis Program

The analysis program is written so that the starting and ending times between which the analysis is to take place can be indicated as a data entry. The program assumes that the packed binary tapes which contain the data to be analyzed exist in edited form. Data cards are used to indicate the total time period, the sample average time, if desired, and the type of analysis (i.e., 1--Side by Side Receiver Analysis, 2--LOP Measurement Accuracy Analysis, 3--Uncorrected Differential OMEGA Error Analysis, 4--Skywave Corrected Differential OMEGA Error Analysis). In addition, a set of chart phase values for each station pair is read in. (See Figure H-1 for the data card format instructions.) The output statistics referenced to each chart value of LOP phase include hourly mean, an unbiased estimate of hourly standard deviation, hourly rms error, and number of sample points included in each hourly statistic. A seasonal (normally 24 hours) statistic for the period of interest is also included as output.

Incorporated in the analysis routine is the ability to specify a sample averaging time over which ten second samples are to be averaged before the

(4 cards for TYPE 1 and 2 Analysis; 7 cards for TYPE 3 or 4 Analysis)

Card 1: FORMAT(715)

Words 1 and 2: Start analysis hour and day (GMT)

Words 3 and 4: Stop analysis hour and day (GMT)

Word 5: Year

Word 6: Number of samples over which to average data points

Type 1 or 2 Analysis

Cards 2-4: FORMAT (8F10.0)

Words 1-24: Chart LOP phase

Type 3 or 4 Analysis

Cards 2-4: FORMAT (8F10.0)

Words 1-24: Chart LOP phase for (receiver 1 - receiver 2)

Card 5: FORMAT (I1, A3, I2, I4, 2A3, F7.4)

Word 1: Type of Analysis (1, 2, 3, 4, or 5) [I1]

1 - Side-by-Side Receiver Analysis

2 - LOP Measurement Accuracy Analysis of RCVR 1

3 - Uncorrected Differential Omega Error Analysis

4 - Skywave-Corrected Differential Omega Error Analysis

5 - LOP Measurement Accuracy Analysis of RCVR 2

Word 2: Month of Analysis Run [A3]

Word 3: Day of Analysis Run [I2]

Word 4: Year of Analysis Run [I4]

Word 5: Location of RCVR 1 [A3]

Word 6: Location of RCVR 2 [A3]

Word 7: Frequency of Tracor Receiver [F7.4]

Cards 6-11: Print-out labels (these are always the same)

Figure H-1. Input data format for analysis program (OMEGA).

EXPERIMENTAL CONDITIONS		FORTRAN STATEMENT										IDENTIFICATION SEQUENCE
1	2	3	4	5	6	7	8	9	10	11	12	13
	1.4	2.6.4	1.3	2.6.8	3	- Analysis from hour 14 day 264	to hour 13 day 268 with 3 samples averaged					
	All zeros for side-by-side analysis	0	0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0	0
	1.10.0.0	1.97.3	1.3.6	1.0.2	1.0.2	- Type 1 analysis done on Nov. 1, 1974 with both receivers at Langley and Tracor set at 10.2 kHz.						
	NOR, TRI	- FRQ	1.0.2	NOR, TRI	- FRQ	1.3.6	NOR, TRI	- FRQ	1.1.3	NOR, HAW	- FRQ	1.0.2
	NOR, HAW	- FRQ	1.3.6	NOR, HAW	- FRQ	1.1.3	NOR, NDK	- FRQ	1.0.2	NOR, NDK	- FRQ	1.3.6
	NOR, NDK	- FRQ	1.1.3	TRI, HAW	- FRQ	1.0.2	TRI, HAW	- FRQ	1.3.6	TRI, HAW	- FRQ	1.1.3
	TRI, NDK	- FRQ	1.0.2	TRI, NDK	- FRQ	1.3.6	TRI, NDK	- FRQ	1.1.3	HAW, NDK	- FRQ	1.0.2
	HAW, NDK	- FRQ	1.3.6	HAW, NDK	- FRQ	1.1.3	TRACOR	- CHANNELS	1.2	TRACOR	- CHANNELS	1.3
	TRACOR	- CHANNELS	1.4	TRACOR	- CHANNELS	2.3	TRACOR	- CHANNELS	2.4	TRACOR	- CHANNELS	3.4

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various statistics are calculated. This can vary from no sample averaging up to 10 minute averaging. Averaging is accomplished using a sliding window type sample average. The last N raw data samples are averaged to provide a new smoothed sample at each 10 second sample point. For each successive smoothed sample a new raw data sample is accumulated into the average as the earliest of the N raw data samples is dropped. Whenever bad data are encountered, the average sample output is interrupted for an N sample time duration. Thus bad data do not bias the sample averaging process. The resulting sample set represents the result of low pass filtering of the raw data. Appendix I describes this sample averaging filter in more detail.

The LOP phase measurements on the packed binary tapes are scaled on the interval (0,100) centicycles (cec) at the particular frequency of measurement. The true value of the variable of interest, (0,100) cec, is input to the particular analysis program and unbiased measurement are calculated. The resulting unbiased measurements on the interval (-100, +100) cec are then scaled to the interval (-50, +50) cec. The assumption made in the statistical analysis is that the deviation of the measurement from the true value will be less than or equal to 50 cec. The mean calculated is then an average difference between the data and the assumed true value. The standard deviation is a measure of the deviation from the mean of the data and the rms difference is a measure of the deviation from the assumed true value.

Requested run time should be 400 seconds on the CDC-6600 machine. Requested core is 42000 words and O/S calls are 3000.

Figure H-2 is a listing of the analysis program. Figure H-3 summarizes the various types of analysis that can be made with program OMEGA.

Fig. H-2. Analysis program listing and flow chart.

```

PROGRAM OMEGA(TAPE10,INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7)
C
C TAPE 7 WILL BE A MAGTAPE HOLDING RESULTS FOR IBM 370
C
C*****C
C THIS PROGRAM IS DESIGNED TO READ IN COMPARISON DATA AND FIND C
C HOURLY AND SEASONAL MEANS AND STANDARD DEVIATIONS. C
C THE MAIN PROGRAM JUST READS IN TIME PARAMETERS AND THEN CALLS C
C VARIOUS SUBROUTINES. C
C*****C
COMMON/SUB/ IREAD, IPRINT, ITAPN, IEND, IERR,
1 IHR, IDAY, JHR, JDAY, IYR, ISAMP, ESTMN(24),
2 IFLAG(24), ITRAN(4), NSEND, I80
COMMON/SUB1/ IOLD, ISTOP, ISECH, ISECD
C*****
C READ IN START TIME--IHR, IDAY STOP TIME--JHR, JDAY AND YEAR--IYR
C THEN CHANGE TIME TO SECONDS.
C ALSO READS IN NO. OF MINUTES (1-5) FOR AVERAGE SAMPLING.
C*****
REWIND 7
READ (IREAD,5000) IHR, IDAY, JHR, JDAY, IYR, ISAMP
READ(IREAD,4990) I80
4990 FORMAT (I5)
5000 FORMAT (6I5)
READ (IREAD,5001) (ESTMN(K),K=1,24)
5001 FORMAT (8F10.0)
IOLD= IDAY*ISECD + IHR*ISECH
ISTOP= JDAY*ISECD + JHR*ISECH
CALL GETSTR
C*****
C CHECK FOR SUBROUTINE ERRORS.
IF (IERR) 200,50,200
50 IF (IEND) 200,150,200
150 CALL STAT
IF (IERR) 200,300,200
200 WRITE (IPRINT,5010) IHR, IDAY, IYR, JHR, JDAY, IYR,
5010 FORMAT (1H , 5X, 38HDESIRED TIME SPAN WAS (IN HR-DAY-YR) ,
1 12,1H-,13,1H-,14, 4H TO , 12,1H-,13,1H-,14)
300 CALL EXIT
END

```



```

      SUBROUTINE GETSTR
C*****
C      THIS SUBROUTINE READS THE FIRST INPUT RECORD CALLS UNPACK-
C      RTN TO UNPACK HEADER INFO CHECKS THE HEADER THEN FINDS
C      THE FIRST GOOD RECORD THAT STARTS AT THE BEGINNING HOUR.
C*****
      COMMON/SUB1/ IREAD, IPRINT, ITAPN, IEND, IERR,
      1   IHR, IDAY, JHR, JDAY, IYR, ISAMP, ESTMN(24),
      2   IFLAG(24), ITRAN(4), NSEND, I80
      COMMON/SUB1/ IOLD, ISTOP, ISECH, ISECD
      COMMON/SUB2/ IRLK(512), IA(5), IB(5), IC(5), ID(5), NO, IMAX
      COMMON/SUB3/ DATA(24), ITIME, IREC, IUNPK, IEST
      COMMON/SUB4/ XMN(24), XSTD(24), RMS(24), IFST,
      1   ICNT(24), ITOT(24), ISEAS, NHR, NDAY, KEY
      INTEGER FLD, EOF
      INEQ= IOLD + ISECH
      100 READ (ITAPN) IRLK
      IF (EOF, ITAPN) 100, 150
C*****
C      GET HEADER-INFO. FROM UNPACK-RTN. DATA FIELDS ARE
C      1.ID OF RECV1/ 2.TAPE NO. OF RECV1/ 3.ID OF RECV2/
C      4.TAPE NO. OF RECV2/ 5.DATE IN YEARS.
C      PARAMETERS ARE
C      IA(5)--BEG. BIT OF EACH DATA FIELD-- 0,5,15,20,30.
C      IB(5)--LENGTH OF EACH FIELD-- 5,10,5,10,10.
C      IC(5)--DATA WORD CONTAINING THIS FLD--1,1,1,1,1.
C      NC=5--NO. OF FLD-CALLS. IUNPK=0--GOES TO 1ST. PART OF UNPACK.
C*****
      150 CALL UNPACK
      IF (ID(3)) 200, 1000, 200
      200 IF (ID(5)-IYR) 1100, 250, 1100
      250 IENDTM= IRLK(2)
C*****
C      CHECK FINAL TIME IN THIS BLOCK WITH STARTING TIME.
      IDIFF= IENDTM - IOLD
      IF (IDIFF) 100, 350, 300
      300 IF (IDIFF-9) 350, 350, 310
      310 IF (IENDTM-INFW) 320, 320, 1200
      320 IREC= 1
      GO TO 400
      350 IREC= IMAX
      400 IUNPK=1

      410 CALL UNPACK
C*****
C      IF THIS IS THE 1ST. GOOD RECORD, RETURN ELSE CONTINUE TO READ.
      IF (IEND) 2000, 450, 2000
      450 IF (ITIME-IOLD) 500, 1500, 1500
      500 IREC= IREC + 1
      GO TO 410
C*****
C      ERROR CONDITIONS.
      1000 WRITE (IPRINT, 6000) (ID(I), I=1, 4)
      6000 FORMAT (1H0, 4X, 36HINCORRECT TAPE WAS MCUNTED. RECV1--, 15,
      1 10HTAPE NO.--, 17, 7HRECV2--, 15, 10HTAPE NO.--, 17)
C*****
C      TEMP. STEP. IF TAPE ISN T A MERGED TAPE, PROG. SHOULD END.
      GO TO 200
      1100 WRITE (IPRINT, 6010) IYR, ID(5)
      6010 FORMAT (1H0, 5X, 40HINPUT YEAR AND YR. ON TAPE DON T MATCH--, 2I7)
      GO TO 1300
      1200 WRITE (IPRINT, 6020) IHR
      6020 FORMAT (1H0, 5X, 32HNO DATA FOUND FOR STARTING HR.--, 1I0)
      1300 IERR=1
      1450 REWIND ITAPN
      RETURN
      1500 CONTINUE

```

```

2000 KEY=AND(FLD(40,4,IBLK(1)),15)
C*****C
C
C HAS TAPE BEEN EDITED IF KEY=0 THEN NO. C
C
C*****C
2005 NSEND= 0
C*****C
C
C SET ALL TRANSMITTER INDICATORS TO ON. (NSEND=0). C
C THEN STATISTICS CAN BE RUN ON UNEDITED DATA. PRINT OUT C
C WILL INDICATE RESULTS ARE FOR UNEDITED DATA. C
C
C*****C
DO 2015 K=1,4
2015 ITRAN(K)= 0
RETURN
C*****C
C
C EDITED TAPE. SET ANY ITRAN=1 FOR TRANSMITTER NOT ON. C
C
C*****C
2020 LOC= 39
ISUM= 0
DO 2040 K=1,4
LOC= LOC + 1
IND=AND(FLD(LOC,1,IBLK(1)),1)
IF (IND) 2025,2030,2025
2025 ITRAN(K)= 0
GO TO 2035
2030 ITRAN(K)= 1
2035 ISUM= ISUM + IND
2040 CONTINUE
C*****C
C
C SET NSEND=0 IF ALL TRANSMITTERS ON. OTHERWISE NSEND=1. C
C
C*****C
IF (ISUM-4) 2045,2050,2045
2045 NSEND= 1
RETURN
2050 NSEND= 0
RETURN
END

```

```

      SUBROUTINE UNPACK
C*****
C      THIS SUBROUTINE UNPACKS DATA FIELDS, USING THE FLD-FUNCTION. C
C      IT ALSO READS THE INPUT TAPE WHEN MORE DATA IS NEEDED. C
C      ARGUMENTS FOR FLD-FUNCTION ARE C
C      ARG1--FIRST BIT OF DATA. C
C      ARG2--LENGTH OF DATA. C
C      ARG3--NO. OF THE WORD THAT CONTAINS THE DATA. C
C      IUNPK=0--UNPACKS HEADER FIELDS. IUNPK=1--UNPACKS CECS-FIELDS. C
C*****
      COMMON/SUB/ IREAD, IPRINT, ITAPN, IEND, IERR,
1     IHR, IDAY, JHR, JDAY, IYR, ISAMP, ESTMN(24),
2     IFLAG(24), ITRAN(4), NSEND, I80
      COMMON/SUB2/ IBLK(512), IA(5), IB(5), IC(5), ID(5), NO, IMAX
      COMMON/SUB3/ DATA(24), ITIME, IREC, IUNPK, IEST
      INTEGER FLD, EOF
      DATA DIV/100., IMULT/15/, ISKIP/3/
      IF ((IUNPK) 1000,100,300
100  DO 150 I=1,NO
      J=IC(I)
      ID(I)= FLD(IA(I), IB(I), IBLK(J))
150  CONTINUE
      GO TO 1500
300  IF (IMAX-IREC) 310,400,400
310  READ (ITAPN) IBLK
      IF (EOF,ITAPN) 1400,320
320  IREC=1
C*****
C      IN EACH BLOCK, WORDS 1 2 ARE HEADER-INFO. THEN THERE ARE
C      34 15-WORD RECORDS. DIFFERENCES BETWEEN STATION PAIRS ARE
C      STORED IN WORDS 8-15.
C*****
400  IWORD= (IREC-1) * IMULT + ISKIP
      ITIME=IBLK(IWORD)
      IWORD= IWORD + 6
      IEST=AND(FLD(56,1,IBLK(IWORD)),1)
      DO 450 J=1,24,3
      IWORD= IWORD + 1
      TERM1= FLD( 0,20, IBLK(IWORD))
      TERM2= FLD(20,20, IBLK(IWORD))
      TERM3= FLD(40,20, IBLK(IWORD))
      DATA(J) = TERM1/DIV

      DATA(J+1) = TERM2/DIV
      DATA(J+2) = TERM3/DIV
450  CONTINUE
      DO 451 J=1,24
      IF(DATA(J) .GT. -500.00) GO TO 451
      IEST=1 $ GO TO 1500
451  CONTINUE
      GO TO 1500
C
1000  WRITE (IPRINT,5000) IUNPK
5000  FORMAT (IHO, 5X, 14HERRCR-- IUNPK=,I5)
      IERR=1
1400  IEND=1
      REWIND ITAPN
1500  RETURN
      END

```

```

SUBROUTINE STAT
C*****C
C THIS SUBROUTINE FINDS MEANS AND STD. DEVIATIONS FOR EACH HOUR, C
C THEN FOR THE TOTAL TEST-PERIOD. DATA IS STORED AS FOLLOWS C
C DATA(1)--NOR,TRI*10.2 DATA(2)--NOR,TRI*13.6 DATA(3)--NOR,TRI*11.3 C
C DATA(4)--NOR,HAW*10.2 DATA(5)--NOR,HAW*13.6 DATA(6)--NOR,HAW*11.3 C
C DATA(7)--NOR,NDK*10.2 DATA(8)--NOR,NDK*13.6 DATA(9)--NOR,NDK*11.3 C
C DATA(10)--TRI,HAW*10.2 DATA(11)--TRI,HAW*13.6 DATA(12)--TRI,HAW*11.3 C
C DATA(13)--TRI,NDK*10.2 DATA(14)--TRI,NDK*13.6 DATA(15)--TRI,NDK*11.3 C
C DATA(16)--HAW,NDK*10.2 DATA(17)--HAW,NDK*13.6 DATA(18)--HAW,NDK*11.3 C
C DATA(19)--TRACOR 1-2 DATA(20)--TRACOR 1-3 DATA(21)--TRACOR 1-4 C
C DATA(22)--TRACOR 2-3 DATA(23)--TRACOR 2-4 DATA(24)--TRACOR 3-4 C
C*****C
COMMON/SUR/ IREAD, IPRINT, ITAPN, IEND, IERR,
1 IHR, IDAY, JHR, JDAY, IYR, ISAMP, ESTMN(24),
2 IFLAG(24), ITRAN(4), NSEND, I80
COMMON/SUB1/ IOLD, ISTOP, ISECH, ISECD
COMMON/SUB3/ DATA(24), ITIME, IREC, IUNPK, IEST
COMMON/SUB4/ XMN(24), XSTD(24), RMS(24), IFST,
1 ICNT(24), ITOT(24), ISEAS, NHR, NDAY, KEY
DIMENSION PART1(24), PART2(24), SSUM(24), SSQR(24),
1 TSUM(24), TSQR(24), IPNT(24), KK(24), SAMPAC(24,60)
DATA PART1/24*0.0/, PART2/24*0.0/, SSUM/24*0.0/, SSQR/24*0.0/,
ITSUM/24*0.0/, TSQR/24*0.0/, IPNT/24*1/, KK/24*1/
DO 50 K=1,24
DO 50 J=1,60
50 SAMPAC(K,J)= 0.0
C*****C
C DO WE WANT SAMPLE AVERAGING C
C IF SO THEN ISAMP N.EQ. 0. C
C*****C
IF (ISAMP-1) 130,130,100
C*****C
C TO INITIALIZE, SET SAMPLE AVG ACCUMULATOR POINTERS OT ONE. C
C*****C
100 DO 120 K=1,24

120 IPNT(K)= 1
130 IUNPK=1
140 INEXT= IOLD + ISECH
150 IF (ITIME-IOLD) 1000,250,200
C*****C
C THIS RECORD SHOULD BE ACCUMULATED WITH PRESENT HOUR. C
C PART1--PARTIAL SUMS OF MEAN ACCUMULATOR. C
C SSUM- HOURLY MEAN ACCUM. TSUM- TOTAL PERIOD MEAN ACCUM. C
C PART2--PARTIAL SUMS FOR STD DEV. ACCUMULATOR. C
C SSQR--HOURLY STD ACCUM. TSQR--TOT PERIOD STD ACCUM. C
C ICNT/ TOTALS OF READINGS/HOUR. ITOT-- TOTALS FOR SEASON. C
C IREC-- RECORD COUNTER FOR UNPACK. C
C ARRAYS- C
C IPNT(24)- INDICATES THAT SAMPLE ACCUMULATOR IS TO BE C
C STARTED. THIS OCCURS EITHER AT BEGINNING OF SEASON OR AFTER C
C BAD DATA. 0 MEANS ACCUMULATORS ARE WORKING. 1 MEANS START C
C ICNT(24)- HOURLY SAMPLE COUNTER OF SAMPLES USED IN FORMING C
C STATISTICS C
C IFLAG(24)- BAD DATA FLAG. IF 1 THEN DISREGARD DATA. IF 0 C
C THEN DATA IS NOT TO BE DISREGARDED UNLESS TRANS IS DOWN C
C KK(24)- SAMPLE COUNTER IN EACH SAMPLE AVG ACCUMULATOR. C
C SAMPAC(24,60)- SAMPLE ACCUMULATORS FOR SAMPLE AVERAGING. C
C*****C

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```

200 IF (ITIME-INEXT) 250,500,500
C*****C
C
C      SCALE DATA ON -49.9, +50.0 RANGE.
C
C*****C
250 CALL XMEAN
    IF (ISAMP-1) 258,258,710
C*****C
C      DOES THE CURRENT RECORD HAVE ANY BAD DATA
C      IF SO THEN TEST N.EQ.0.
C
C*****C
258 IF (IEST) 310,259,310
C*****C
C      START HERE FOR NO SAMPLE AVG. AND NO BAD DATA.
C
C
C*****C
259 DO 300 K=1,24
260 PART1(K)= PART1(K) + DATA(K)
    PART2(K)= PART2(K) + (DATA(K)**2)
    ICNT(K)= ICNT(K) + 1
    IF (MOD(ICNT(K),90)) 300,270,300
270 SSUM(K)= SSUM(K) + PART1(K)
    SSQR(K)= SSQR(K) + PART2(K)
    PART1(K)= 0.0
    PART2(K)= 0.0
300 CONTINUE
    GO TO 490
C*****C
C      START HERE FOR NO SAMPLE AVG. AND SOME BAD DATA.
C
C*****C
310 DO 350 K=1,24
    IF (IFLAG(K)) 350,320,350
320 PART1(K)= PART1(K) + DATA(K)
    PART2(K)= PART2(K) + (DATA(K)**2)
    ICNT(K)= ICNT(K) + 1
    IF (MOD(ICNT(K),90)) 350,340,350
340 SSUM(K)= SSUM(K) + PART1(K)
    SSQR(K)= SSQR(K) + PART2(K)
    PART1(K)= 0.0
    PART2(K)= 0.0
350 CONTINUE
490 IREC= IREC + 1
    CALL UNPACK
    IF (IEND) 500,150,500
C*****C
C      END OF HOUR. COMPUTE HOURLY STATISTICS.
C      MEAN= (1/N) * SUM OF X(I)
C      STD DEV= SQRT((1/(N-1))*(SUM(X(I)**2)-(1/N)*(SUM(X(I))**2))
C      RMS ERROR= SQRT(1/N * SUM(X(I)**2))
C
C*****C
500 DO 600 K=1,24
    IF (ICNT(K)) 503,600,503
503 XCNT= ICNT(K)

    CONST1= 1. / XCNT
    CONST2= 1. / (XCNT-1.)

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C*****C
C
C      IF ISEAS= 0, HOURLY STATISTICS.  OTHERWISE SEASONAL STAT.  C
C
C*****C
      IF (ISEAS) 510,530,510
510  TEMTOT= TSUM(K)
      TEMSQR= TSQR(K)
      GO TO 550
530  TEMTOT= SSUM(K) + PART1(K)
      TEMSQR= SSQR(K) + PART2(K)
550  XMN(K)= CONST1 * TEMTOT
      TEMP= TEMSQR - CONST1 * (TEMTOT**2)
      STD = CONST2 * TEMP
      XSTD(K)= SQRT(STD)
      RMS(K)= SQRT(CONST1 * TEMSQR)
      IF (ISEAS) 600,590,600
590  TSUM(K)= TSUM(K) + TEMTOT
      TSQR(K)= TSQR(K) + TEMSQR
600  CONTINUE
C*****C
C
C      IF THIS IS END OF TIME PERIOD, CALL PRTO AND EXIT.  C
C      OTHERWISE REPEAT.  C
C
C*****C
      IF (ISEAS) 610,630,610
610  CALL PRTO
      GO TO 1500
630  NDAY= IOLD / ISECD
      NHR= (IOLD - (NDAY * ISECD)) / ISECH
      CALL PRTO
      DO 632 K=1,24
632  ITOT(K)= ITOT(K) + ICNT(K)
      IOLD= INEXT
      INEXT= INEXT + ISECH
      IF (IOLD-ISTOP) 640,640,700
640  IF (IFND) 700,645,700
C*****C
C
C      CLEAR ACCUMULATOR ARRAYS AND BEGIN NEW HOUR.  C
C
C
C*****C
645  DO 650 K=1,24
      ICNT(K)= 0
      PART1(K)= 0.0
      PART2(K)= 0.0
      SSLM(K)= 0.0
      SSQR(K)= 0.0
      XMN(K)= 0.0
      XSTD(K)= 0.0
      RMS(K)= 0.0
650  CONTINUE
      GO TO 150
C*****C
C
C      HAVE COMPLETED THE SEASONAL STATISTICS.  C
C
C*****C
700  DO 705 K=1,24
705  ICNT(K)= ITOT(K)
      ISEAS=1
      GO TO 500
710  IF (IEST) 801,711,801

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```

C*****C
C                                     C
C      START HERE WITH SAMPLE AVG.  NO BAD DATA.      C
C                                     C
C*****C
711 DO 750 K=1,24
715 IF (IPNT(K)) 720,720,717
717 KK(K)= 1
      N= KK(K)
      SAMPAC(K,N)= DATA(K)
      KK(K)= KK(K) + 1
      GO TO 745
720 N= KK(K)
      IF (N-ISAMP) 725,730,730
725 SAMPAC(K,N)= DATA(K)
      KK(K)= (KK(K) + 1)
      GO TO 745
730 SAMPAC(K,N)= DATA(K)
      SUM= 0.0
      DO 740 I=1,ISAMP

      SUM= SUM+ SAMPAC(K,I)
      NK= I + 1
      IF (I - ISAMP) 733,735,735
733 SAMPAC(K,I)= SAMPAC(K,NK)
      GO TO 740
735 SAMPAC(K,I)= 0.0
740 CONTINUE
      PART1(K)= PART1(K) + (SUM / ISAMP)
      PART2(K)= PART2(K) + ((SUM / ISAMP)**2)
      ICNT(K)= ICNT(K) + 1
      IF (MOD(ICNT(K),90)) 745,741,745
741 SSUM(K)= SSUM(K) + PART1(K)
      SSQR(K)= SSQR(K) + PART2(K)
      PART1(K)= 0.0
      PART2(K)= 0.0
745 IPNT(K)= 0
750 CONTINUE
      GO TO 490
C*****>*****C
C                                     C
C      START HERE WITH SAMPLE AVG.  SCME BAD DATA.      C
C                                     C
C*****C
801 DO 850 K=1,24
      IF (IFLAG(K)) 804,805,804
804 IPNT(K)= 1
      GO TO 850
805 IF (IPNT(K)) 820,820,810
810 KK(K)=1
      N= KK(K)
      SAMPAC(K,N)= DATA(K)
      KK(K)= KK(K) + 1
      GO TO 845
820 N=KK(K)
      IF (N-ISAMP) 825,830,830
825 SAMPAC(K,N)= DATA(K)
      KK(K)= KK(K) + 1
      GO TO 845
830 SAMPAC(K,N)= DATA(K)
      SUM= 0.0
      DO 840 I=1,ISAMP
      SUM= SUM + SAMPAC(K,I)
      NK= I + 1

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```

      IF (I-ISAMP) 833,835,835
833  SAMPAC(K,I)= SAMPAC(K,NK)
      GO TO 840
835  SAMPAC(K,I)= 0.0
840  CONTINUE
      PART1(K)= PART1(K) + (SUM / ISAMP)
      PART2(K)= PART2(K) + ((SUM / ISAMP)**2)
      ICNT(K)= ICNT(K) + 1
      IF (MOD(ICNT(K),90)) 845,841,845
841  SSUM(K)= SSUM(K) + PART1(K)
      SSQR(K)= SSQR(K) + PART2(K)
      PART1(K)= 0.0
      PART2(K)= 0.0
845  IPNT(K)= 0
850  CONTINUE
      GO TO 490
C*****C
C                                     C
C      CANNOT FIND DESIGNATED HOUR.  REWIND TAPE AND FLAG.      C
C                                     C
C*****C
1000 WRITE (IPRINT,5000) ITIME,IOLD
5000 FORMAT (I11,44HTIME ON TAPE LESS THAN CURRENT HOUR.  END JOB, 2I10)
      IEND= 1
      GO TO 500
1500 REWIND ITAPN
      RETURN
      END

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SUBROUTINE XMEAN
COMMON/SUB/ TREAD, IPRINT, ITAPN, IEND, IERR,
1 IHR, IDAY, JHR, JDAY, IYR, ISAMP, ESTMN(24),
2 IFLAG(24), ITRAN(4), NSEND, I80
COMMON/SUB3/ DATA(24), ITIME, IREC, IUNPK, IEST
DIMENSION NTRAN(4,12)
DATA NTRAN/1,1,4,7,2,2,5,8,3,3,6,9,4,10,10,13,5,11,11,14,6,12,12,1
15,7,13,16,16,8,14,17,17,9,15,18,18,19,19,20,21,20,22,22,23,21,23,
224,24/, XMIN/-50.0/, XMAX/+50.0/
C*****C
C
C ARE THERE ANY TRANSMITTERS DOWN C
C
C*****C
IF (NSEND) 110,170,110
C*****C
C
C IF ANY TRANSMITTER IS DOWN. ENTER HERE. C
C ARE THERE ANY OTHER BAD DATA C
C
C*****C
110 IF (IEST) 115,145,115
C*****C
C
C SOME TRANSMITTER DOWN. SOME OTHER BAD DATA. START LOOP HERE. C
C
C*****C
115 DO 220 K=1,24
DO 135 J=1,4
IF (ITRAN(J)) 120,135,120
120 DO 130 L=1,12
IF (K-NTRAN(J,L)) 130,125,130
125 IFLAG(K)= 1
GO TO 220
130 CONTINUE
135 CONTINUE
IF (DATA(K)+400) 140,140,190
140 IFLAG(K)= 1
GO TO 220
190 DIFFR= (AMOD(DATA(K),100.)) - ESTMN(K)
IF (DIFFR) 195,215,205
195 IF (DIFFR-XMIN) 200,200,215

200 DIFFR= DIFFR + 100.
GO TO 215
205 IF (DIFFR-XMAX) 215,215,210
210 DIFFR= DIFFR - 100.
215 DATA(K) = DIFFR
IFLAG(K) = 0
220 CONTINUE
RETURN
C*****C
C
C SOME TRANSMITTER DOWN. NO OTHER BAD DATA. START LOOP HERE. C
C
C*****C
145 DO 320 K=1,24
DO 165 J=1,4
IF (ITRAN(J)) 150,165,150
150 DO 160 L=1,12
IF (K-NTRAN(J,L)) 160,155,160
155 IFLAG(K)= 1
IEST= 1
GO TO 320
160 CONTINUE
165 CONTINUE

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290 DIFFR= (AMOD(DATA(K),100.)) - ESTMN(K)
  IF (DIFFR) 295,315,305
295 IF (DIFFR-XMIN) 300,300,315
300 DIFFR= DIFFR + 100.
  GO TO 315
305 IF (DIFFR-XMAX) 315,315,310
310 DIFFR= DIFFR - 100.
315 DATA(K)= DIFFR
  IFLAG(K)= 0
320 CONTINUE
  RETURN
C*****C
C
C      NO TRANSMITTER DOWN. ENTER HERE.
C      ARE THERE ANY BAD DATA
C
C*****C
170 IF (IFST) 175,185,175
C*****C
C
C      NO TRANSMITTER DOWN. SCME OTHER BAD DATA. START LOOP HERE.
C
C*****C
175 DO 420 K=1,24
  IF (DATA(K)+400) 180,180,390
180 IFLAG(K)= 1
  GO TO 420
390 DIFFR= (AMOD(DATA(K),100.)) - ESTMN(K)
  IF (DIFFR) 395,415,405
395 IF (DIFFR-XMIN) 400,400,415
400 DIFFR= DIFFR + 100.
  GO TO 415
405 IF (DIFFR-XMAX) 415,415,410
410 DIFFR= DIFFR - 100.
415 DATA(K)= DIFFR
  IFLAG(K)= 0
420 CONTINUE
  RETURN
C*****C
C
C      NO TRANSMITTER DOWN. NO OTHER BAD DATA. START LOOP HERE.
C
C*****C
185 DO 520 K=1,24
490 DIFFR= (AMOD(DATA(K),100.)) - ESTMN(K)
  IF (DIFFR) 495,515,505
495 IF (DIFFR-XMIN) 500,500,515
500 DIFFR= DIFFR + 100.
  GO TO 515
505 IF (DIFFR-XMAX) 515,515,510
510 DIFFR= DIFFR - 100.
515 DATA(K)= DIFFR
  IFLAG(K)= 0
520 CONTINUE
  RETURN
END

```

```

SUBROUTINE PRTO
COMMON/SUB/ IREAD, IPRINT, ITAPN, IEND, IERR,
1   IHR, IDAY, JHR, JDAY, IYR, ISAMP, ESTMN(24),
2   IFLAG(24), ITRAN(4), NSEND, I80
COMMON/SUB2/ IBLK(512), IA(5), IB(5), IC(5), ID(5), NO, IMAX
COMMON/SUB4/ XMN(24), XSTD(24), RMS(24), IFST,
1   ICNT(24), ITOT(24), ISEAS, NHR, NDAY, KEY
DIMENSION LABEL(5,24)
C*****C
C   THIS SUBROUTINE READS PRINT LABEL POINTERS FOR FIRST PAGE C
C   HEADING. STATISTICAL ANALYSIS FOR EITHER C
C   1. SIDE BY SIDE RECEIVER ANALYSIS C
C   OR 2. LOP MEASUREMENT ACCURACY ANALYSIS OF RECEIVER 1 C
C   OR 3. UNCORRECTED DIFFERENTIAL OMEGA ERROR ANALYSIS C
C   OR 4. SKY-WAVE CORRECTED DIFFERENTIAL OMEGA ERROR ANALYSIS C
C   OR 5. TYPE 2 TEST USING RECEIVER 2 C
C   OUTPUT INCLUDES DATE OF RUN, TOTAL DATA PERIOD ANALYZED, C
C   HOUR AND HOURLY STATISTICS, DATA SAMPLE AVERAGING, AND C
C   RECEIVER POSITION LOCATIONS. C
C   INPUT DATA C
C   LABEL(M,N) M=1,5, J=1,24  FORMAT 20A4 C
C   TYPE OF OUTPUT ICUT I1 C
C   MONTH OF ANALYSIS KMONTH A3 C
C   DAY OF ANALYSIS KDAY I2 C
C   YEAR OF ANALYSIS KYEAR I4 C
C   RECEIVER 1 LOCATION LOC1 A3 C
C   RECEIVER 2 LOCATION LOC2 A3 C
C   TRACOR FREQ TRAFQ F7.4 C
C*****C
C   PRINT COMMON HEADING C
C*****C
5001 FORMAT (1H1,46X,28HANGLEY RESEARCH CENTER DATA,/34X,52HGROUND-BAS
1FD DIFFERENTIAL OMEGA TEST (G-DGT) PROGRAM,/)
99 WRITE(IPRINT,5001)
IF (IFST) 110,100,110
100 READ (IREAD,5002) ICUT,KMONTH,KDAY,KYEAR,LOC1,LOC2,TRAFQ

5002 FORMAT (I1,A3,I2,I4,2A3,F7.4)
READ (IREAD,5003) ((LABEL(I,J),I=1,5),J=1,24)
5003 FORMAT (20A4)
IF (ISAMP) 105,103,105
103 NSAMP= 10
GO TO 110
105 NSAMP= ISAMP * 10
C*****C
C   WHAT TYPE OF ANALYSIS C
C*****C
110 IF (ICUT-2) 130,140,120
120 IF (ICUT-4) 150,160,140
130 WRITE (IPRINT,5017) LOC1, TRAFQ, ID(2), ID(4)
5017 FORMAT (1H ,45X,30HSIDE BY SIDE RECEIVER ANALYSIS,/33X,20HRECEIVER
1S LOCATED AT,2X,A3,10X,12HTRACOR FREQ=,F4.1,3HKHZ,/33X,15HPCVR 1--
2TAPE NR,17,5X,15HRCVR 2--TAPE NR,17,/)
GO TO 170
140 WRITE (IPRINT,5004)
5004 FORMAT (1H ,42X,33HLOP MEASUREMENT ACCURACY ANALYSIS)
IF (ICUT-3) 143,150,146
143 WRITE (IPRINT,5005) LOC1,TRAFQ, ID(2)

```

```

5005 FORMAT (1H ,37X,14HRECEIVER 1 AT ,A3,10X,12HTRACOR FREQ=,F4.1,3HKH
12,/37X,15HRCVR 1--TAPE NR,17,/)
GO TO 170
146 WRITE (IPRINT,5006) LOC2,TRAFQ,ID(4)
5006 FORMAT (1H ,37X,14HRECEIVER 2 AT ,A3,10X,12HTRACOR FREQ=,F4.1,3HKH
12,/37X,15HRCVR 2--TAPE NR,17,/)
GO TO 170
150 WRITE (IPRINT,5007)
5007 FORMAT (1H ,37X,45HUNCORRECTED DIFFERENTIAL OMEGA ERROR ANALYSIS)
GO TO 165
160 WRITE (IPRINT,5008)
5008 FORMAT (1H ,34X,52HISKY-WAVE CORRECTED DIFFERENTIAL OMEGA ERROR ANA
1LYSIS)
165 WRITE (IPRINT,5009) LOC1,LOC2,TRAFQ,ID(2),ID(4)
5009 FORMAT (1H ,24X,14HRECEIVER 1 AT ,A3,10X,14HRECEIVER 2 AT ,A3,10X,
112HTRACOR FREQ=,F4.1,3HKHZ,/24X,15HRCVR 1--TAPE NR,17,26X,15HRCVR
22--TAPE NR,17,/)
170 IF (IFST) 175,180,175
175 IF (ISEAS) 180,190,180
180 WRITE (IPRINT,5010) KMONTH,KDAY,KYEAR,ICAY,IHR,JDAY,JHR,IYR

5010 FORMAT (1H ,26X,13HDATE OF ANAL ,A3,1X,12,1X,14,10X,13HTOTAL PERIO
10 ,13,1H-,12,1H-,4H TO ,13,1H-,12,1H-,14,/)
C *****C
C C
C IS HOURLY OR SEASONAL OUTPUT DESIRED C
C C
C *****C
190 IF (ISEAS) 210,200,210
200 WRITE (IPRINT,5011) NDAY,NHR,IYR,NSAMP
5011 FORMAT (1H ,5X,4HDAY ,13,5X,5H HOUR ,12,5X,5HYEAR ,14,5X,27HOUTPUT
11N CECS AT EACH FREQ,5X,28H10 SEC SAMPLES AVERAGED FOR ,13,1X,4HSE
20S,/)
GO TO 220
210 WRITE (IPRINT,5012) NSAMP
5012 FORMAT (1H ,10X,20HTOTAL PERIOD SUMMARY,5X,27HOUTPUT IN CECS AT EA
1CH FREQ,5X,28H10 SEC SAMPLES AVERAGED FOR ,13,1X,4HSECS,/)
220 IF (KEY) 226,224,226
224 WRITE (IPRINT,5013)
5013 FORMAT (1H ,44X,29H***-INPUT TAPE NOT EDITED--**,/)
C *****C
C C
C PRINT ANALYSIS HEADING C
C C
C *****C
226 WRITE (IPRINT,5014)
5014 FORMAT (1H ,5X,12HLOP AND FREQ,13X,11HCHART VALUE,6X,8HRELATIVE,
19X,7HSTD DEV,10X,8HCH VALUE,9X,5HNR OF,/47X,9HDATA MEAN,25X,
28HRMS DEV.,9X,7HSAMPLES)
IFST=1
IF (I80.EQ.1) GO TO 98
GO TO 97
98 I80=I80+1
IPRINT=7
IF (I80.EQ.2) GO TO 99
97 IPRINT=6
DO 300 K=1,24
IF (ICNT(K)) 240,230,240
C *****C
C C
C PRINT RESULTS FOR BAD DATA C
C C
C *****C
230 WRITE (IPRINT,5015) (LABEL(M,K),M=1,5),ESTMN(K),XMN(K),XSTD(K),

```

```

      IRMS(K)
5015 FORMAT (1H,5X,5A4,5X,F7.2,10X,F7.2,10X,F7.2,10X,F7.2,10X,
      1 8HBAD DATA)
      GO TO 300
C*****C
C                                          C
C      PRINT RESULTS FOR GOOD DATA                                          C
C                                          C
C*****C
      240 WRITE (IPRINT,5016) ((LABEL(M,K),M=1,5),ESTMN(K),XMN(K),XSTD(K),
      IRMS(K),ICNT(K))
5016 FORMAT (1H,5X,5A4,5X,F7.2,10X,F7.2,10X,F7.2,10X,F7.2,10X,16)
      IF (180.NE.2) GO TO 300
      WRITE(7,5019)K,NDAY,NHR,((LABEL(M,K),M=1,5),XMN(K),XSTD(K),RMS(K))
5019 FORMAT(3I4,5A4,3F7.2)
      300 CONTINUE
      RETURN
      END

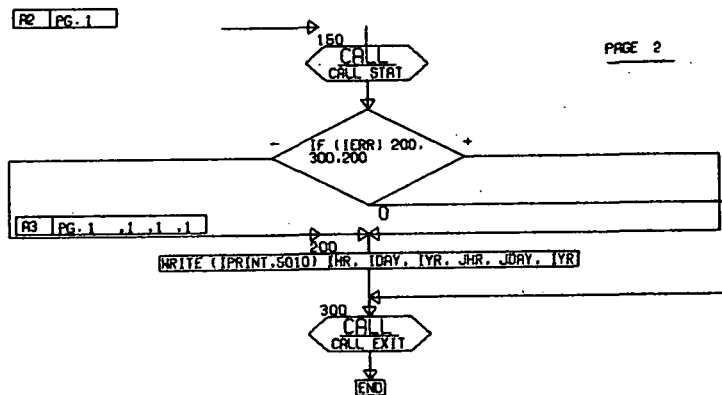
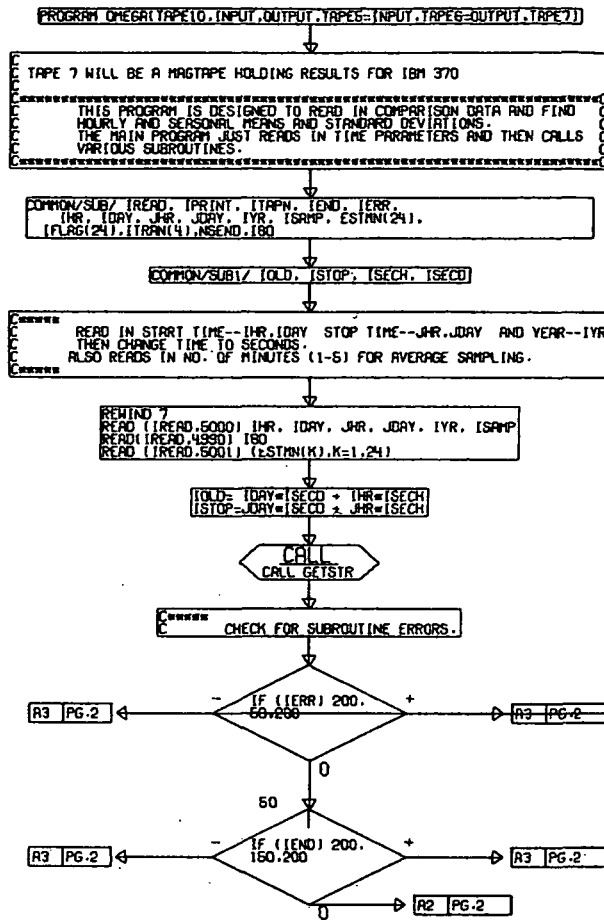
```

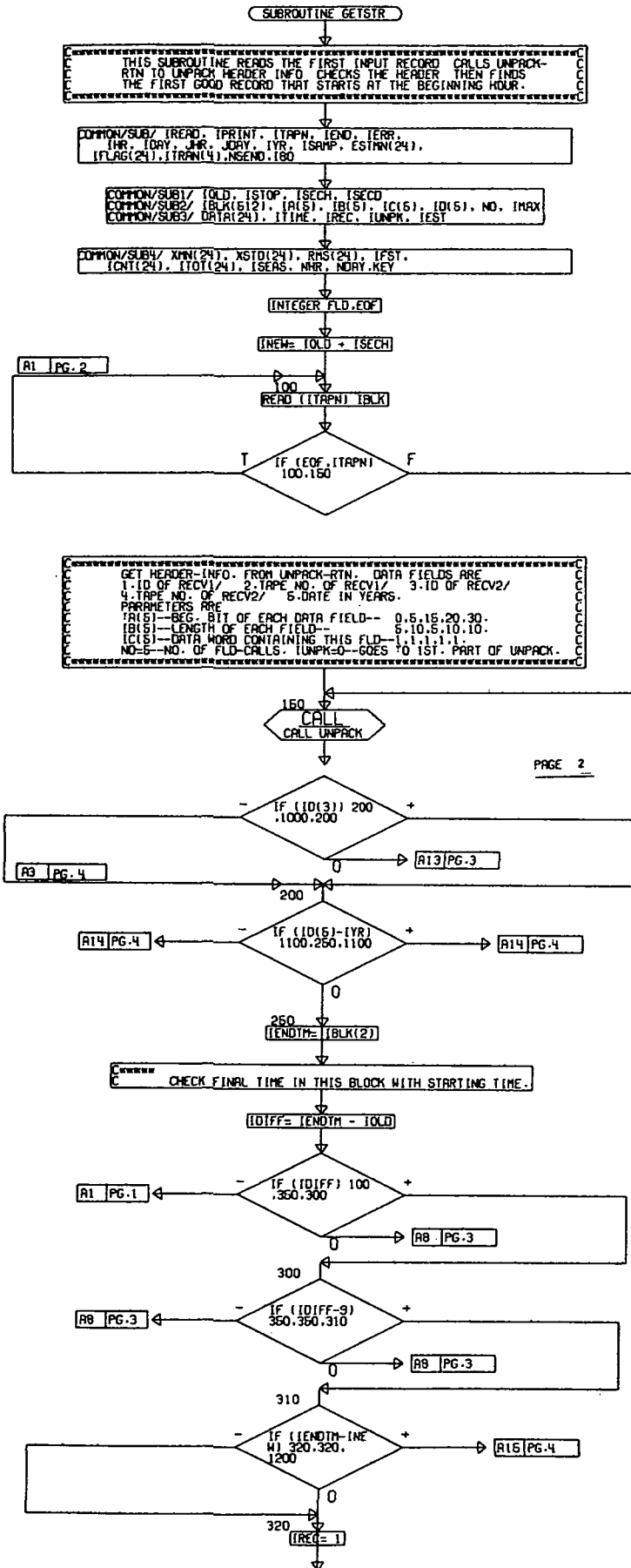
BLOCK DATA

```

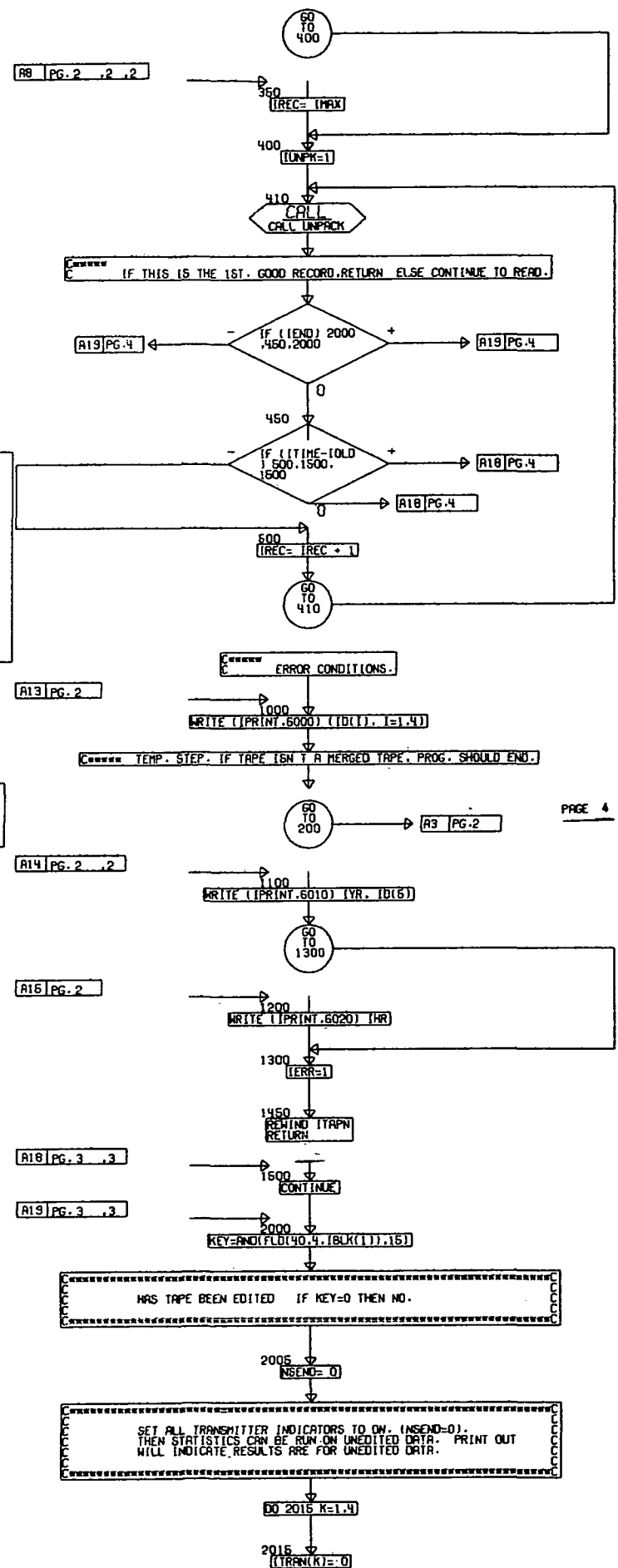
COMMON/SUB/ IREAD, IPRINT, ITAPN, IEND, IERR,
1  IHR, IDAY, JHR, JDAY, IYR, ISAMP, ESTMN(24),
2  IFLAG(24),ITRAN(4),NSEND,180
COMMON/SUB1/ IOLD, ISTOP, ISECH, ISECD
COMMON/SUB2/ IBLK(512), IA(5), IB(5), IC(5), ID(5), NO, IMAX
COMMON/SUB3/ DATA(24), ITIME, IREC, IUNPK, IEST
COMMON/SUB4/ XMN(24), XSTD(24), RMS(24), IFST,
1  ICNT(24), ITOT(24), ISEAS, NHR, NDAY, KEY
DATA IERR/0/, ISECH/3600/, ISECD/86400/, IREAD/5/, IPRINT/6/,
1  ITAPN/10/, IEND/0/
DATA IREC/0/, NO/5/, IUNPK/0/, IA/0,5,15,20,30/, IB/5,10,5,10,10/,
1  IC/5*1/, ID/5*0/, IMAX/34/, IEST/0/, ITRAN/4*0/
DATA XMN/24*0.0/, XSTD/24*0.0/, RMS/24*0.0/, IFST/0/, ICNT/24*0/,
1  ITOT/24*0/, ISEAS/0/, NHR/0/, NDAY/0/, IFLAG/24*0/, NSEND/0/
      END

```

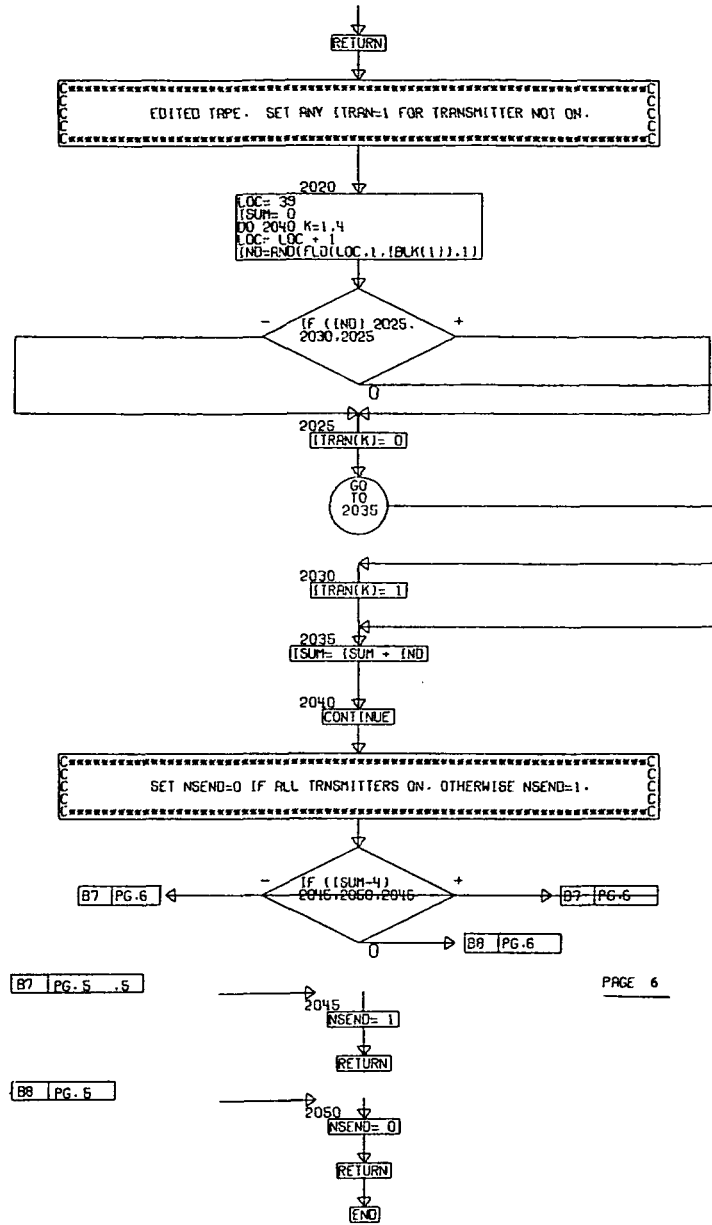




PAGE 2



PAGE 4



SUBROUTINE UNPACK

THIS SUBROUTINE UNPACKS DATA FIELDS, USING THE FLD-FUNCTION.
IT ALSO READS THE INPUT TAPE WHEN MORE DATA IS NEEDED.
ARGUMENTS FOR FLD-FUNCTION ARE
ARG1--FIRST BIT OF DATA.
ARG2--LENGTH OF DATA.
ARG3--NO. OF THE WORD THAT CONTAINS THE DATA.
(UNPK=0--UNPACKS HEADER FIELDS. UNPK=1--UNPACKS DECS-FIELDS.

COMMON/SUB/ IREAD, IPRINT, ITAPN, IEND, IERR,
IHR, IDAY, JHR, JDAY, IYR, ISAMP, ESTANI(24),
IFLAG(24), ITRAP(4), ISEND, IBO

COMMON/SUB/ (BLK(512), IAL(5), IB(5), IC(5), ID(5), NO, IMAX,
COMMON/SUB/ DATA(24), ITIME, IREC, UNPK, IEST
INTEGER FLD, EOF
DATA DIV/100., (MULT/15., (SKIP/3/

IF (UNPK)
1000,100,300

DO 150 I=1,NO
J=IC(I)
ID(I)=FLD(IA(I), IB(I), (BLK(J))

150 CONTINUE

GO TO 1500

IF (IMAX-IREC)
310,400,400

310 READ (ITAPN) (BLK

IF (EOF, ITAPN)
1400,320

320 IREC=1

***** IN EACH BLOCK, WORDS 1,2 ARE HEADER-INFO. THEN THERE ARE
34 15-WORD RECORDS. DIFFERENCES BETWEEN STATION PAIRS ARE
STORED IN WORDS 8-15.

WORD=(IREC-1)*(MULT+SKIP)
ITIME=BLK(WORD)
WORD=WORD+6
IEST=AND(FLD(56,1,(BLK(WORD)),1)
DO 450 J=1,34,3
WORD=WORD+1
TERM1=FLD(0,20,(BLK(WORD))
TERM2=FLD(20,20,(BLK(WORD))
TERM3=FLD(40,20,(BLK(WORD))
DATA(J)=TERM1/DIV
DATA(J+1)=TERM2/DIV
DATA(J+2)=TERM3/DIV

450 CONTINUE

DO 451 J=1,24

IF (DATA(J) .GT.
-500.00)

GO TO 451

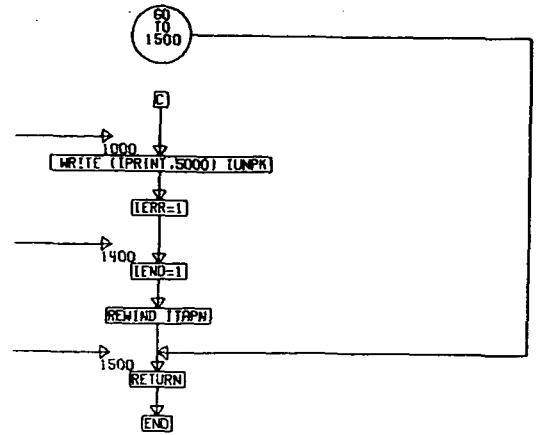
IEST=1 GO TO 1500

451 CONTINUE

R9 PG. 1

R10 PG. 2

R11 PG. 3



PAGE 2

SUBROUTINE STAT

THIS SUBROUTINE FINDS MEANS AND STD. DEVIATIONS FOR EACH HOUR. THEN FOR THE TOTAL TEST PERIOD. DATA IS STORED AS FOLLOWS

DATA(1)---NOR. TR=10.2	DATA(2)---NOR. TR=13.5	DATA(3)---NOR. TR=11.2
DATA(4)---NOR. TR=10.5	DATA(5)---NOR. TR=13.5	DATA(6)---NOR. TR=11.2
DATA(7)---NOR. TR=10.5	DATA(8)---NOR. TR=13.5	DATA(9)---NOR. TR=11.2
DATA(10)---TR=10.5	DATA(11)---TR=13.5	DATA(12)---TR=11.2
DATA(13)---TR=10.5	DATA(14)---TR=13.5	DATA(15)---TR=11.2
DATA(16)---TR=10.5	DATA(17)---TR=13.5	DATA(18)---TR=11.2
DATA(19)---TRACOR 1-2	DATA(20)---TRACOR 1-3	DATA(21)---TRACOR 1-4
DATA(22)---TRACOR 2-3	DATA(23)---TRACOR 2-4	DATA(24)---TRACOR 3-4

COMMON/SUB/ IREQD, IPRINT, IYAPN, IEND, IERN,
IHR, IDAY, IHR, IDAY, IYR, ISAMP, ESTRN(24),
IFLAG(24), ITRAN(4), ISENO, IEND

COMMON/SUB/ IOLD, ISTOP, ISECH, ISECD
COMMON/SUB/ DATA(24), ITIME, IREC, IUNPA, IEST

COMMON/SUB/ KXN(24), XSTD(24), RAS(24), IFST,
ICNT(24), ITOI(24), ISECS, NHR, NDAY, KEY

COMMON/SUB/ PART1(24), PART2(24), SSUM(24), SSOR(24),
ISUM(24), ISOR(24), IPNT(24), KX(24), SAMPAC(24,60)

DATA PART1(24)=0.0, PART2(24)=0.0, SSUM(24)=0.0, SSOR(24)=0.0,
ISUM(24)=0.0, ISOR(24)=0.0, IPNT(24)=1, KX(24)=1

DO 50 K=1, 24
50 SAMPAC(K, J)=0.0

50 SAMPAC(K, J)=0.0

DO WE WANT SAMPLE AVERAGING
IF 50 THEN ISAMP=N.EQ.0.

IF (ISAMP=1) 130, 130, 100
130 PG.2
100 PG.2

PAGE 2

TO INITIALIZE, SET SAMPLE AVG ACCUMULATOR POINTERS TO ONE.

R2 PG.1

DO 120 K=1, 24

120 IPNT(K)=1

R4 PG.1

130 IUNPA=1

R5 PG.5

150 IF (ITIME=10.0) 1, 1000, 100, 200

1000 PG.13
1 PG.3

THIS RECORD SHOULD BE ACCUMULATED WITH PRESENT HOUR.
PART1---PARTIAL SUMS OF MEAN ACCUMULATOR.
SSUM---HOURLY MEAN ACCUM. TSSUM---TOTAL PERIOD MEAN ACCUM.
PART2---PARTIAL SUMS FOR STD DEV. ACCUMULATOR.
SSOR---HOURLY STD ACCUM. ISOR---TOTAL PERIOD STD ACCUM.
ICNT---TOTALS OF RECORDS/HOUR. ITOI---TOTALS FOR SEASON.
IREQD---RECORD COUNTER FOR UNPACK.
ARRAYS
IPNT(24)---INDICATES THAT SAMPLE ACCUMULATOR IS TO BE
STARTED. THIS OCCURS EITHER AT BEGINNING OF SEASON OR AT
BAD DATA. 0 MEANS ACCUMULATORS ARE WORKING. 1 MEANS START
ICNT(24)---HOURLY SAMPLE COUNTER OF SAMPLES USED IN FORMING
STATISTICS
IFLAG(24)---BAD DATA FLAG. IF 1 THEN DISCARD DATA. IF 0
THEN DATA IS NOT TO BE DISCARDED UNLESS TRANS IS DOWN
KX(24)---SAMPLE COUNTER IN EACH SAMPLE AVG ACCUMULATOR.
SAMPAC(24,60)---SAMPLE ACCUMULATORS FOR SAMPLE AVERAGING.

200 IF (ITIME=INEX) 1, 250, 500, 500
1 PG.3
1 PG.5

SCALE DATA ON -99.9, +50.0 RANGE.

97 PG.2

250 CALL XMEAN

IF (ISAMP=1) 258, 258, 710

R13 PG.0

DOES THE CURRENT RECORD HAVE ANY BAD DATA
IF 50 THEN IEST=N.EQ.0.

IF (IEST=1) 310, 259, 310

R13 PG.4

R13 PG.4

START HERE FOR NO SAMPLE AVG. AND NO BAD DATA.

259 DO 300 K=1, 24

260 PART1(K)=PART1(K)+DATA(K)
PART2(K)=PART2(K)+DATA(K)**2
ICNT(K)=ICNT(K)+1

IF (MOD(ICNT(K), 300)) 300, 270, 300

PAGE 4

270 SSUM(K)=SSUM(K)+PART1(K)
SSOR(K)=SSOR(K)+PART2(K)
PART1(K)=0.0
PART2(K)=0.0

300 CONTINUE

GO TO 490

R17 PG.5

START HERE FOR NO SAMPLE AVG. AND SOME BAD DATA.

R13 PG.2

DO 320 K=1, 24

IF (IFLAG(K)) 320, 320, 340

R16 PG.5

R16 PG.5

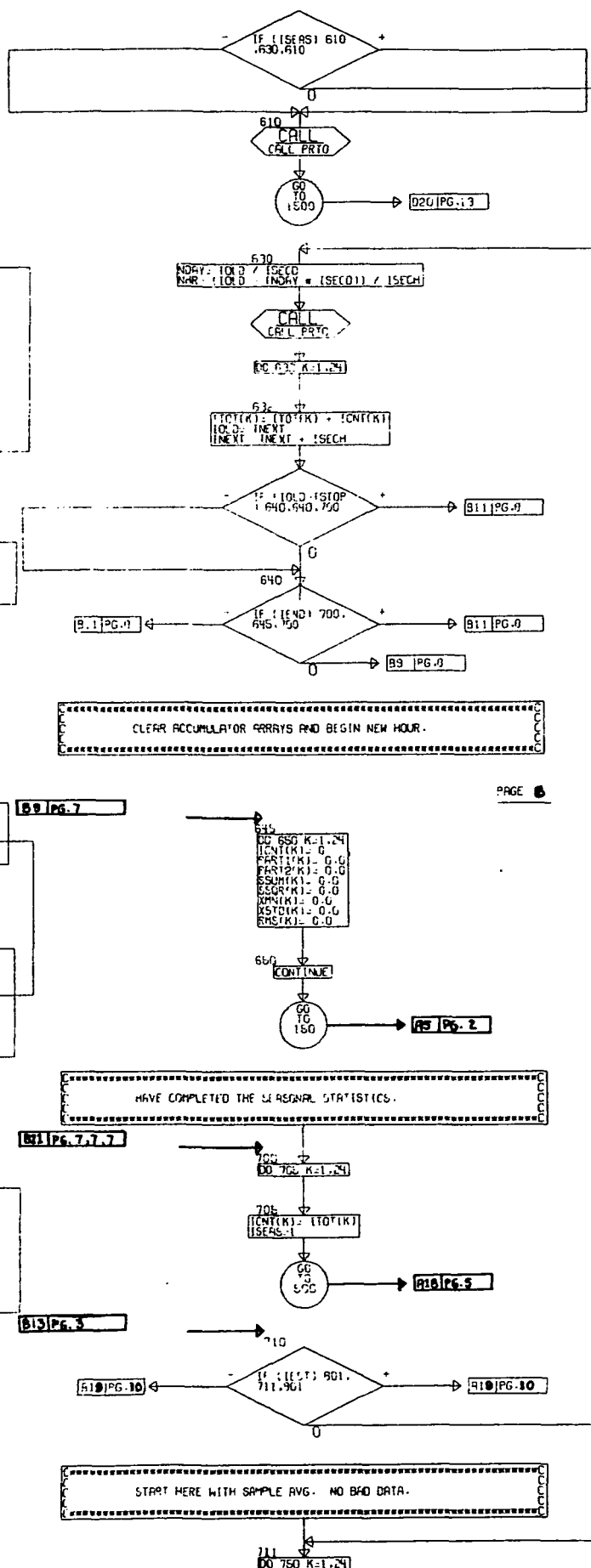
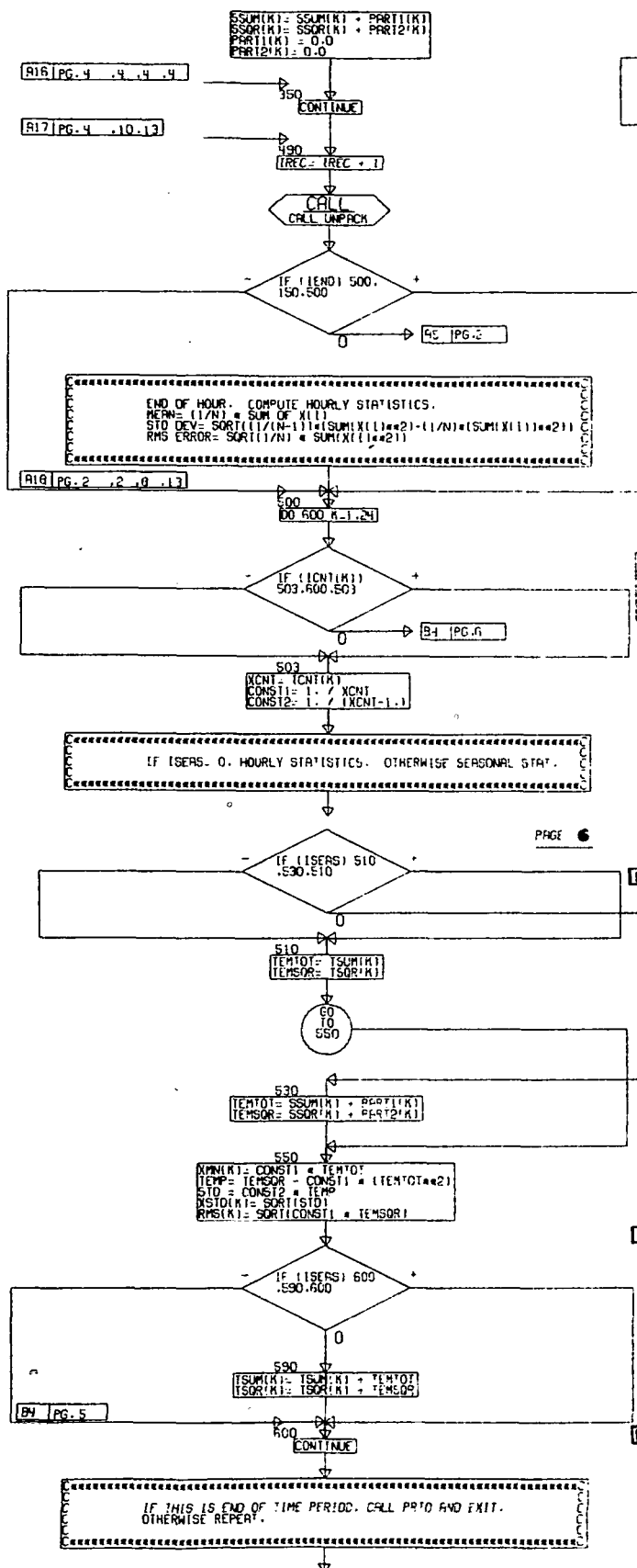
320 PART1(K)=PART1(K)+DATA(K)
PART2(K)=PART2(K)+DATA(K)**2
ICNT(K)=ICNT(K)+1

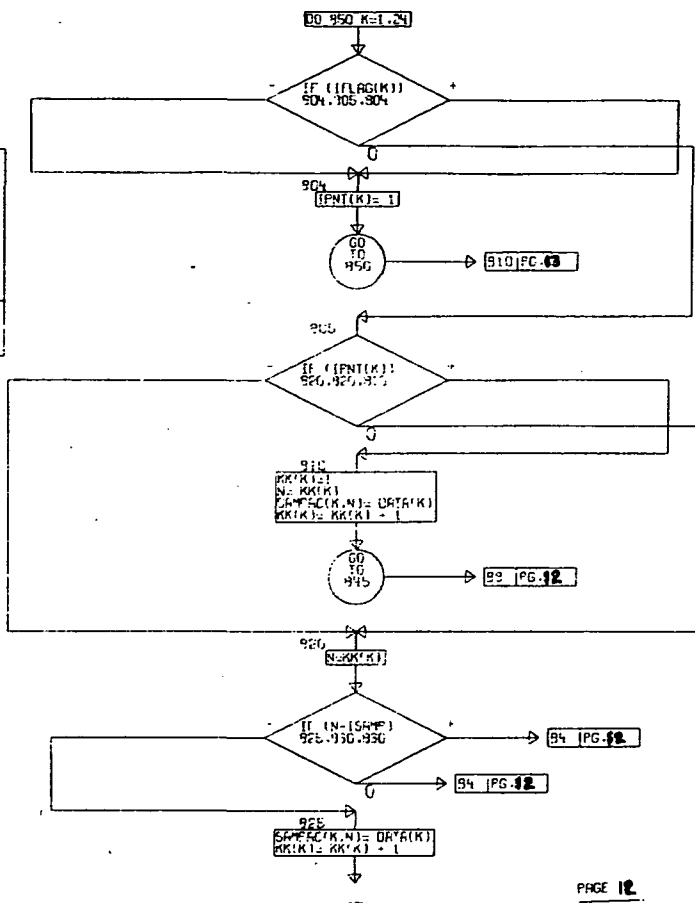
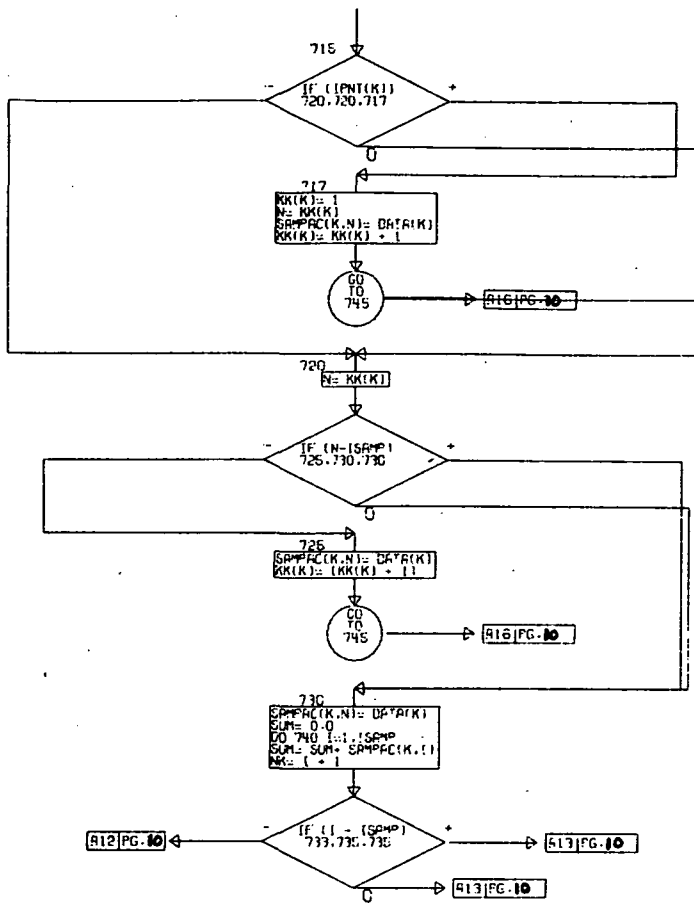
IF (MOD(ICNT(K), 300)) 350, 340, 350

R16 PG.5

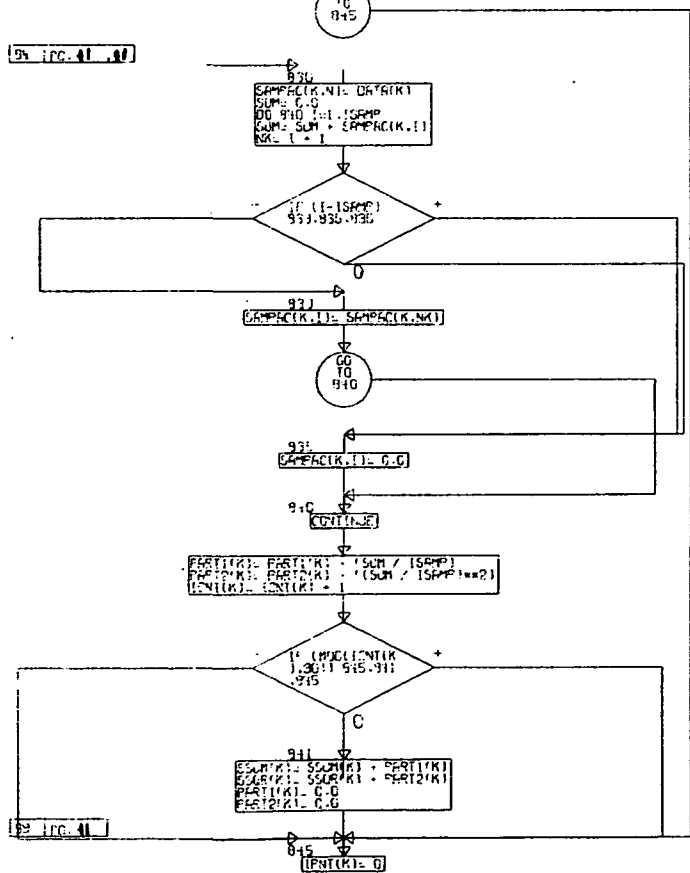
R16 PG.5

340

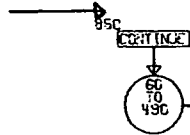




84 PG. 11

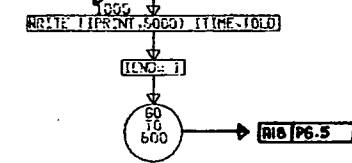


B10/P6.7

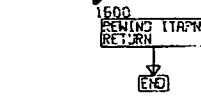


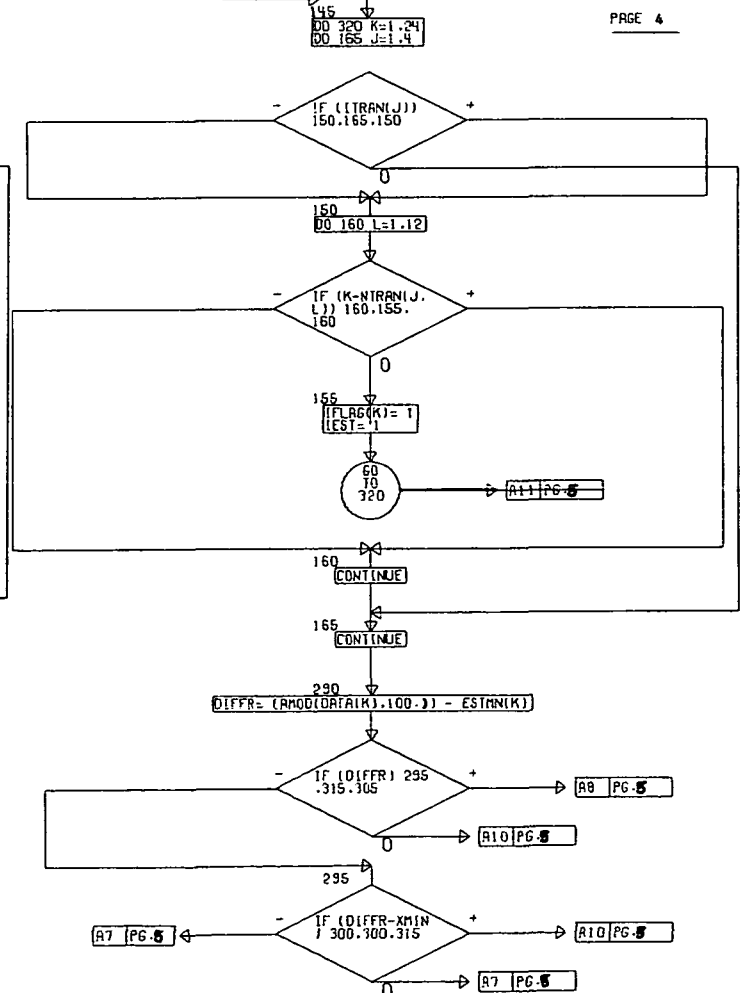
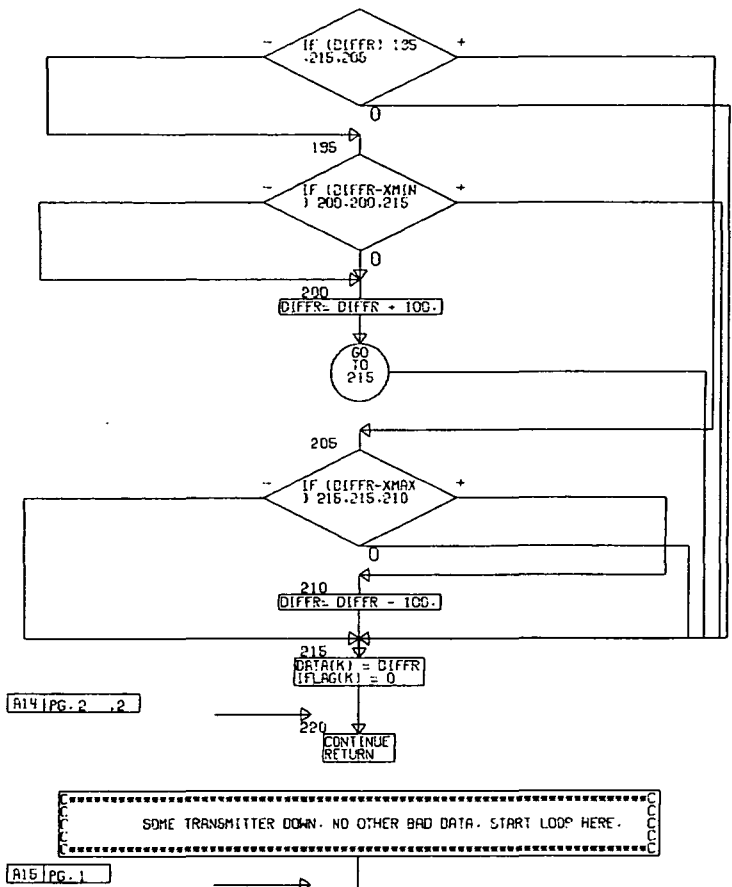
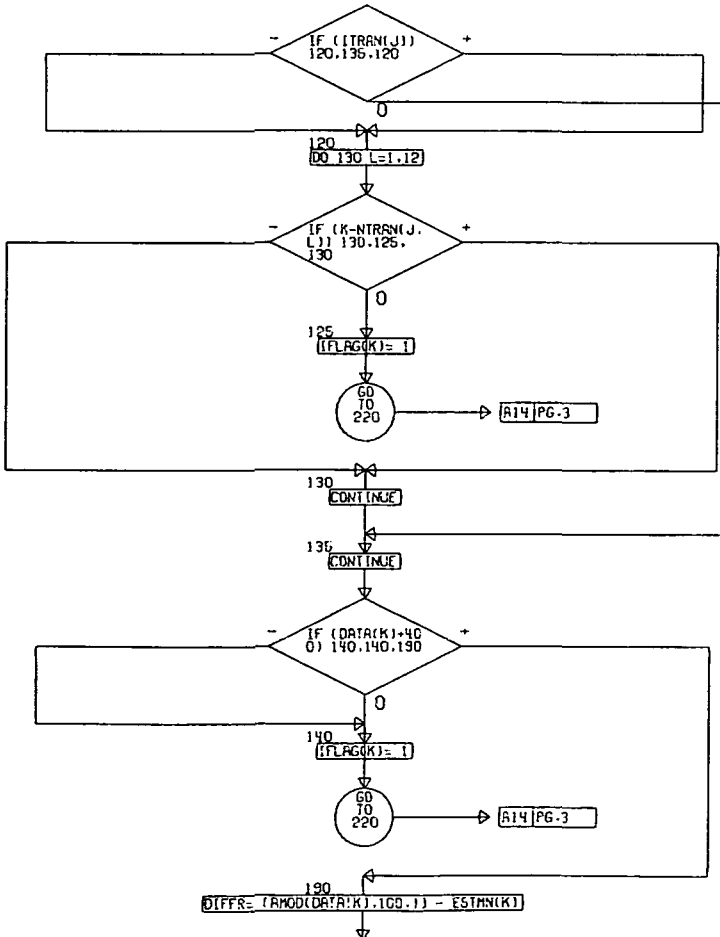
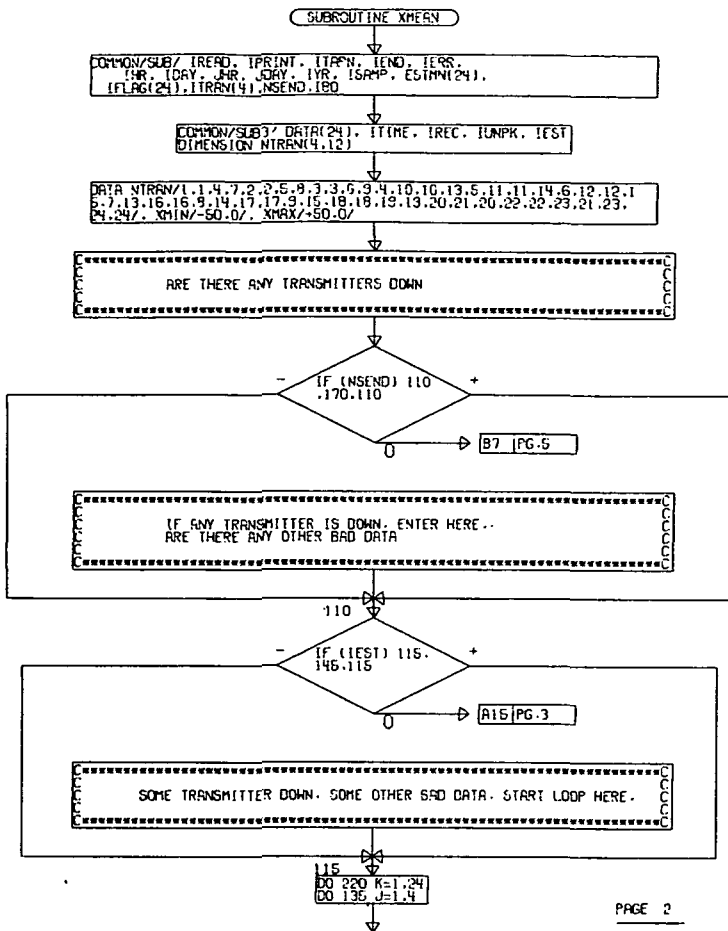
CANNOT FIND DESIGNATED HOUR. REWIND TAPE AND FLAG.

C19/P6.2



D20/P6.11





R7 PG. 4

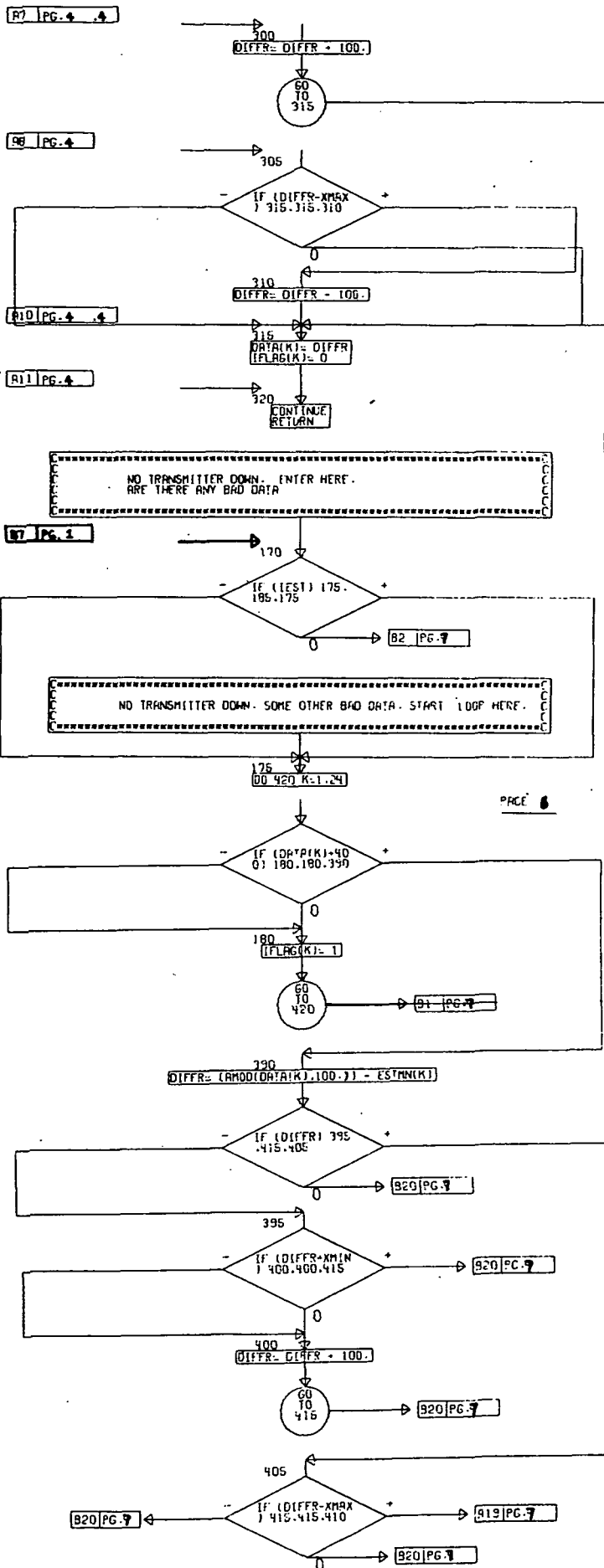
R8 PG. 4

R10 PG. 4

R11 PG. 4

R7 PG. 3

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R19 PG. 6

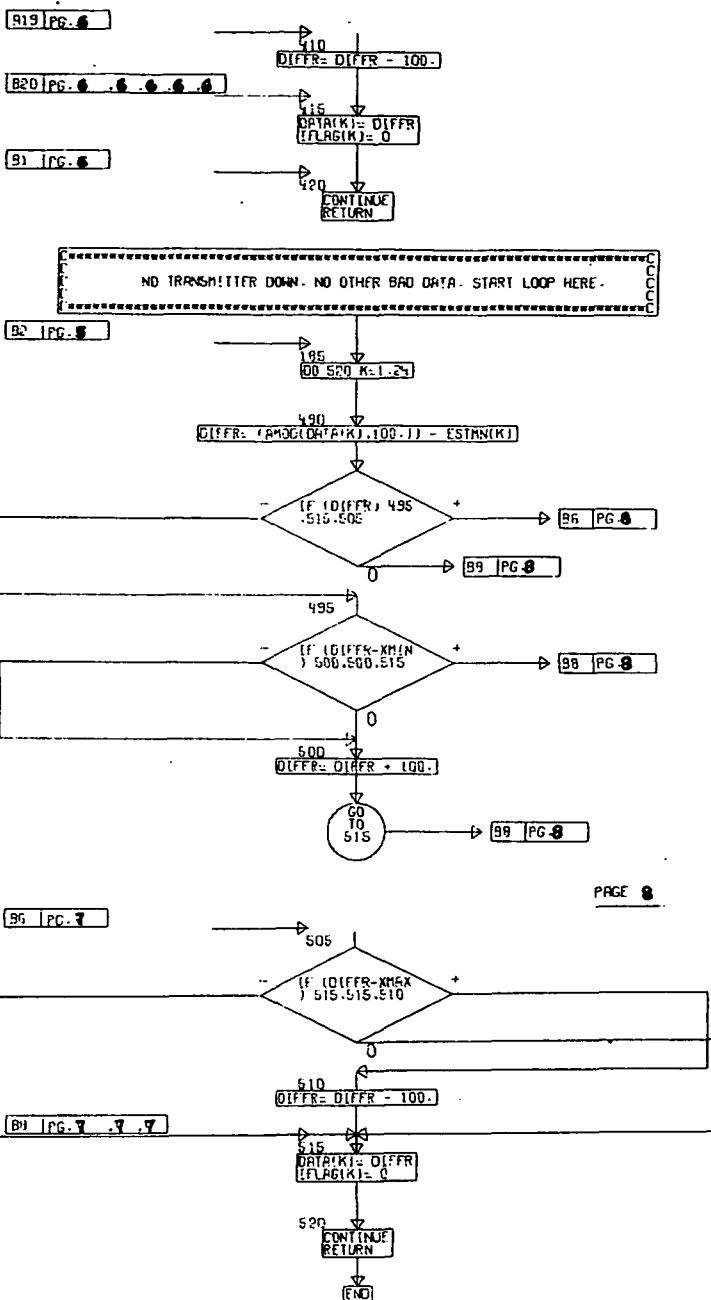
B20 PG. 6

B1 PG. 6

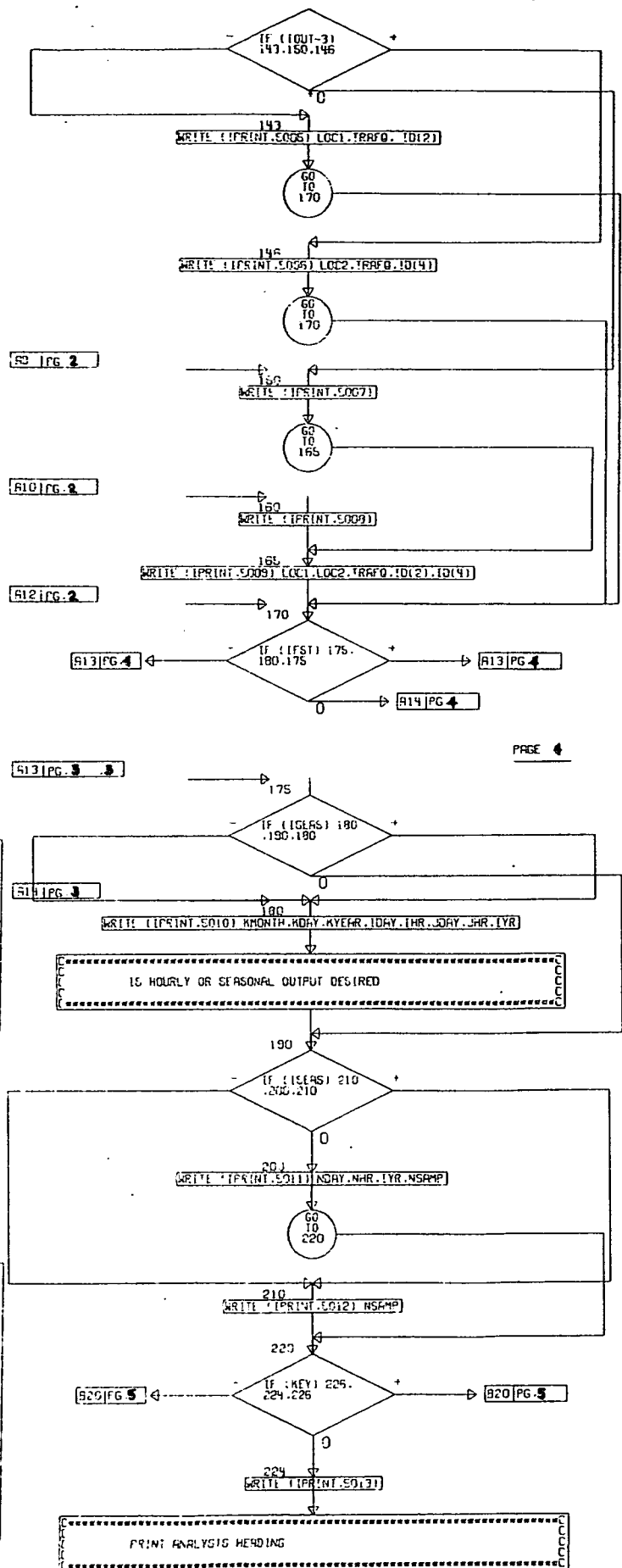
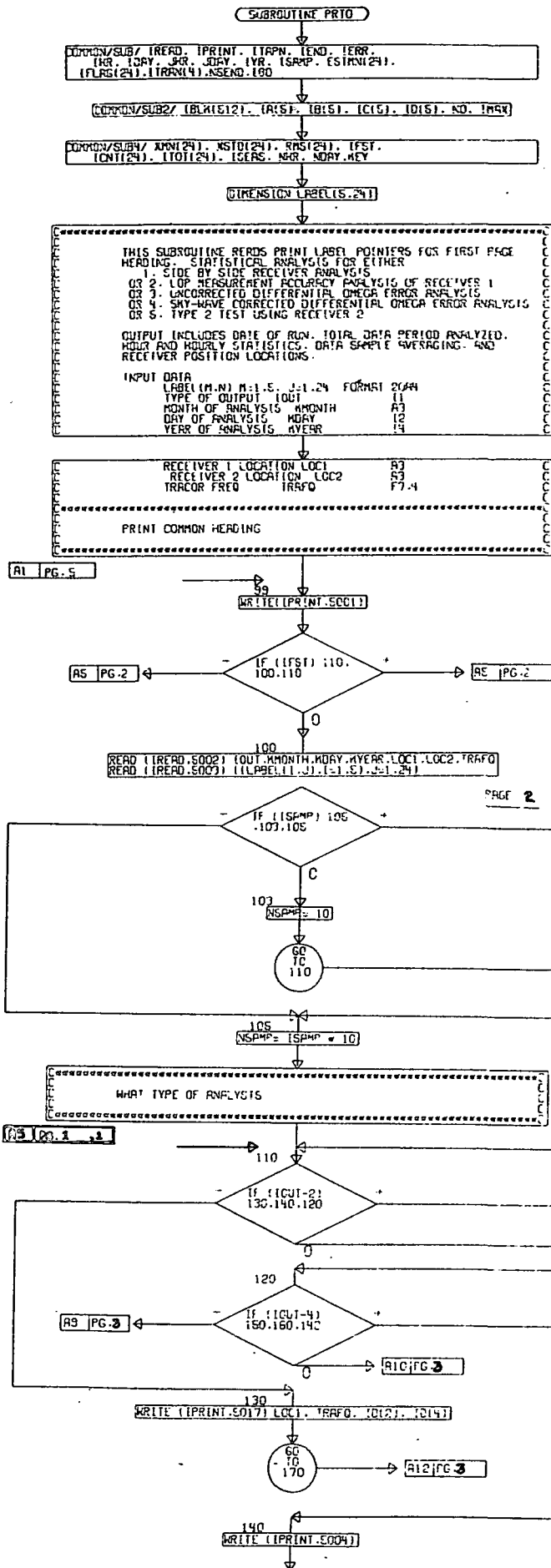
B2 PG. 6

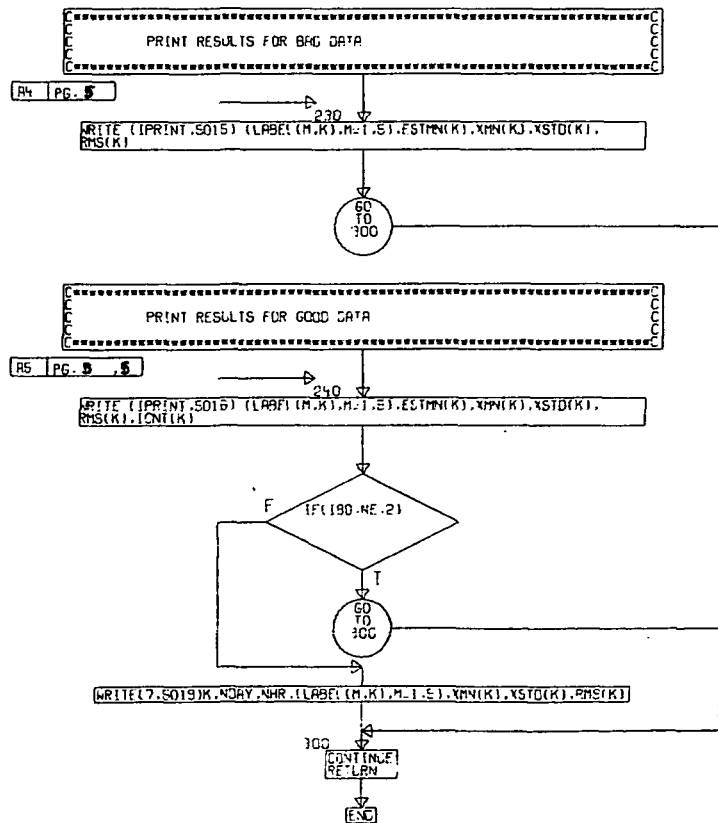
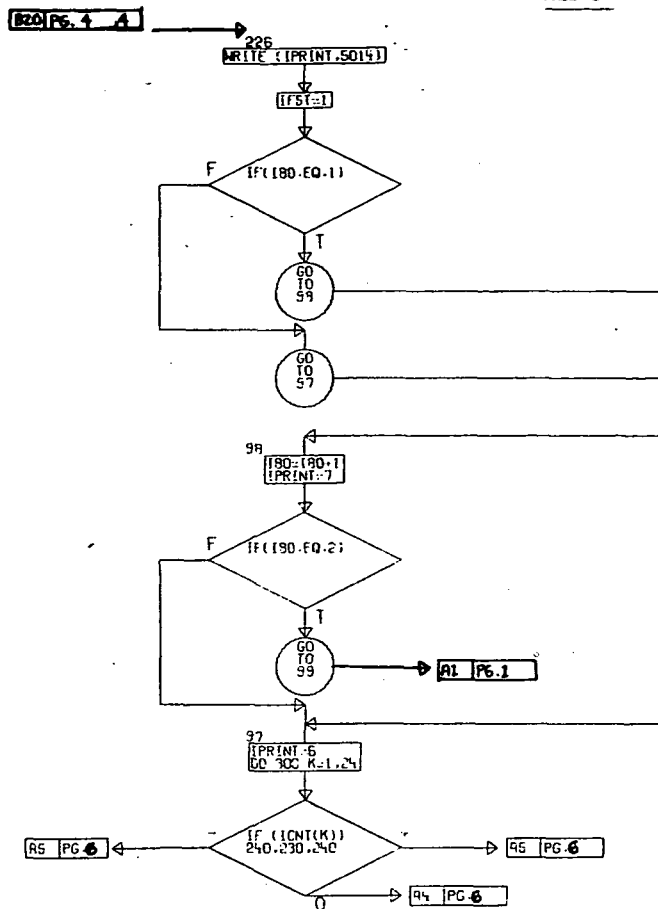
B6 PG. 7

B1 PG. 7



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SIDE-BY-SIDE RECEIVER ANALYSIS

VARIABLE OF INTEREST: LOP difference between receiver for each possible transmitter pair at each frequency.

INPUT: 1) Edited merged packed binary tape with or without time synchronization.
2) Starting time and ending time for analysis.
3) Sample averaging time.
4) True value of LOP difference (ZERO).

OUTPUT: 1) Hourly mean, standard deviation, and rms difference.
2) Number of samples, sample averaging time.
3) Seasonal mean, standard deviation, and rms difference.

LOP MEASUREMENT ACCURACY ANALYSIS

VARIABLE OF INTEREST: Difference between skywave-corrected LOP measurement and chart value.

INPUT: 1) Edited individual packed binary tape with skywave corrections.
2) Starting time and ending time for analysis.
3) Sample averaging time.
4) True value of the LOP (charted value for particular receiver location).

OUTPUT: Same as Side-by-Side Receiver Analysis above.

UNCORRECTED DIFFERENTIAL OMEGA ERROR ANALYSIS

VARIABLE OF INTEREST: LOP difference between receiver measurements less the difference between chart values at each receiver site.

INPUT: 1) Edited merged packed binary tape with or without time synchronization.
2) Starting time and ending time for analysis.
3) Sample averaging time.
4) Estimate of mean LOP difference using difference in chart LOP values between the two receiver sites.

OUTPUT: Same as Side-by-Side Receiver Analysis above.

Figure H-3. Summary of types of analysis available.

SKYWAVE-CORRECTED DIFFERENTIAL OMEGA ERROR ANALYSIS

VARIABLE OF INTEREST: Skywave-corrected LOP difference between receiver measurements less the difference between chart values at each receiver site.

INPUT: 1) Edited merged packed binary tape with or without time synchronization.
2) Starting time and ending time for analysis.
3) Sample averaging time.
4) Estimate of mean LOP difference using difference in chart LOP values between the two receiver sites.

OUTPUT: Same as Side-by-Side Receiver Analysis.

Figure H-3. Continued

APPENDIX I

THE SAMPLE AVERAGING LOW-PASS FILTER

The "sample averaging low pass filter" is used on the OMEGA phase data taken at 10 second sample periods to reduce the variance of these data. This appendix compares the frequency response of this digital filter to a one-pole RC analog filter with equivalent 3 dB points.

The sample averaging involves generating a sequence of sample mean values at the ten second sample positions of the original samples. At each point the original sample is replaced by an average of the preceding N sample values. The value N does not change as the averaging is accomplished. Given an original sample set of M ten second values the output of this digital filter will provide (M - N+1) smoothed ten second values.

The effect of the data averaging routine can be analyzed using a filter described in the time domain by impulse response

$$h(t) = \frac{1}{\tau} [u(t) - u(t + \tau)] \quad , \quad \tau = 10N \text{ sec} \quad ,$$

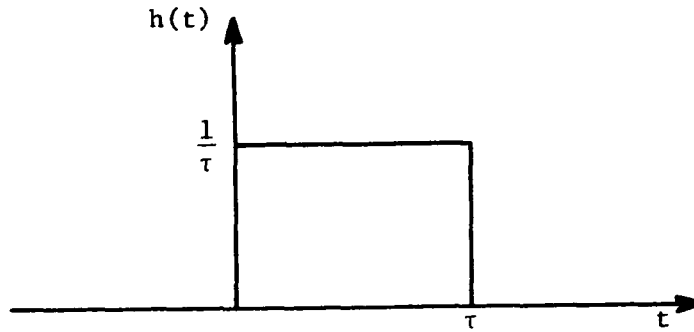


Fig. I-1. Impulse response of the sample averaging filter.

plotted in Figure I-1. The frequency response of this filter can be calculated using the Fourier transform method as

$$H(j\omega) = \frac{1}{\tau} \int_{-\infty}^{\infty} h(t) e^{-j\omega t} dt = \frac{1}{\tau} \int_0^{\tau} e^{-j\omega t} dt$$

or

$$H(j\omega) = [e^{-j\omega\tau/2}] \left[\frac{\sin \omega\tau/2}{\omega\tau/2} \right] .$$

The amplitude response is $A(\omega) = \frac{\sin \omega\tau/2}{\omega\tau/2} = \text{sinc}(f\tau)$, plotted in Figure I-2, and the phase response is $\theta(\omega) = \frac{-\omega\tau}{2}$

where

$$H(j\omega) = A(\omega) e^{j\theta(\omega)} .$$

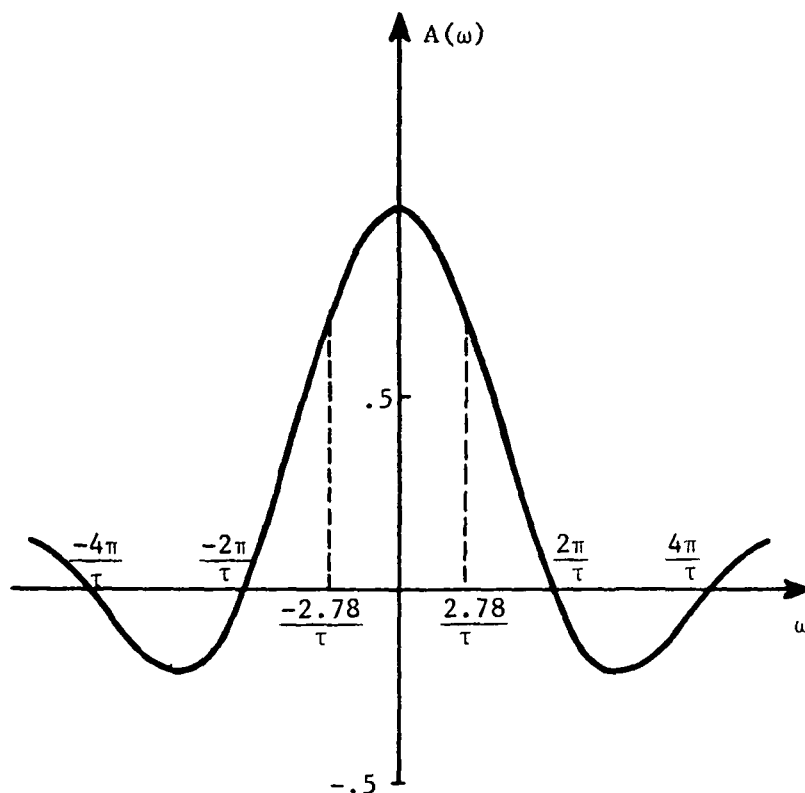


Fig. I-2. Amplitude response of sample averaging filter.

The first zero crossing is at $\omega_1 = \frac{2\pi}{\tau}$. The 3 dB point is at $\omega_{3\text{dB}}$ defined as that ω for which

$$A(\omega_{3\text{dB}}) = \frac{1}{\sqrt{2}} A(\omega = 0) .$$

This occurs at

$$\frac{\omega\tau}{2} = 1.39$$

such that

$$\omega_{3dB} = \frac{2(1.39)}{\tau} = \frac{2.78}{\tau} .$$

An RC filter used as a low-pass filter has a frequency response of

$$H(j\omega) = A(\omega) e^{j\theta(\omega)}$$

where $A(\omega) = \frac{\omega_{RC}}{\sqrt{\omega^2 + \omega_{RC}^2}}$, as shown in Fig. I-3,

and $\theta(\omega) = -\tan^{-1}(\omega/\omega_{RC})$.

$$H(j\omega) = \left(\frac{\omega_{RC}}{j\omega + \omega_{RC}} \right) \quad \text{with} \quad \omega_{RC} = \frac{1}{RC}$$

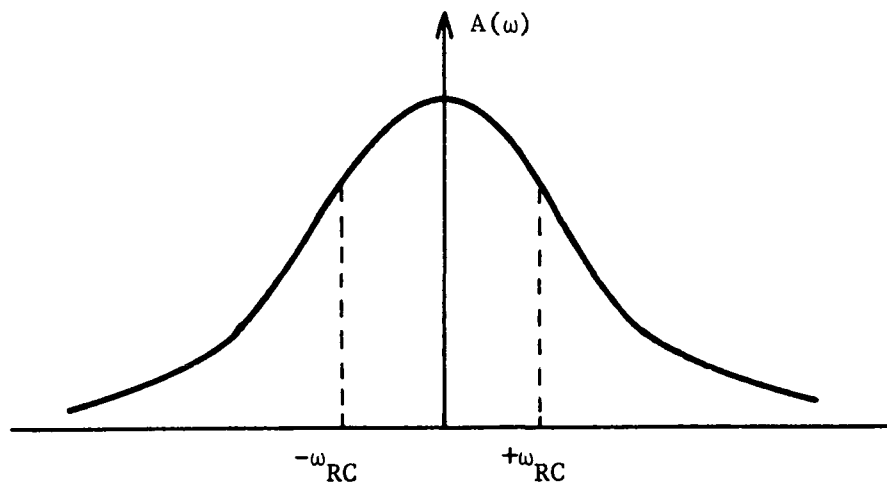


Fig. I-3. The RC filter amplitude response.

Here ω_{RC} represents the "cutoff" frequency where $A(\omega_{RC})$ is $\frac{1}{\sqrt{2}}$ times the $\omega = 0$ value.

If the cutoff frequencies or 3 dB frequencies of the analog RC filter and the digital sample averaging filter are equated then

$$\omega_{3dB} = \omega_{RC}$$

and the sample averaging time of the digital filter can be expressed as a function of the time constant of the RC filter as

$$T_{avg} = 2.78 \tau_{RC} \text{ seconds}$$

where $\tau_{RC} = R \cdot C$ is the time constant of the analog RC filter and T_{avg} is the time over which samples are averaged.

In the time domain the RC filter has an impulse response $\frac{1}{RC} e^{-t/RC}$ which can be compared in the time domain to the impulse response of the sample averaging filter for the equivalent pass band cutoff frequency. These are illustrated in Figure I-4.

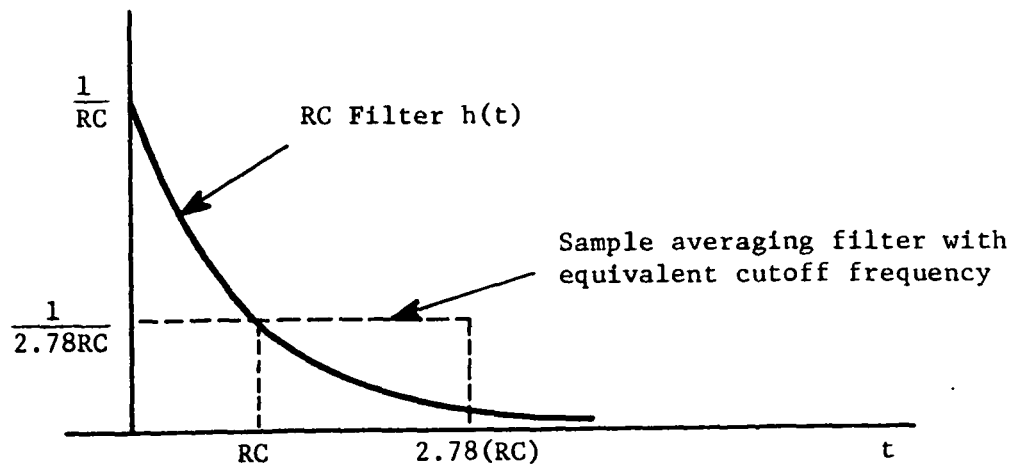
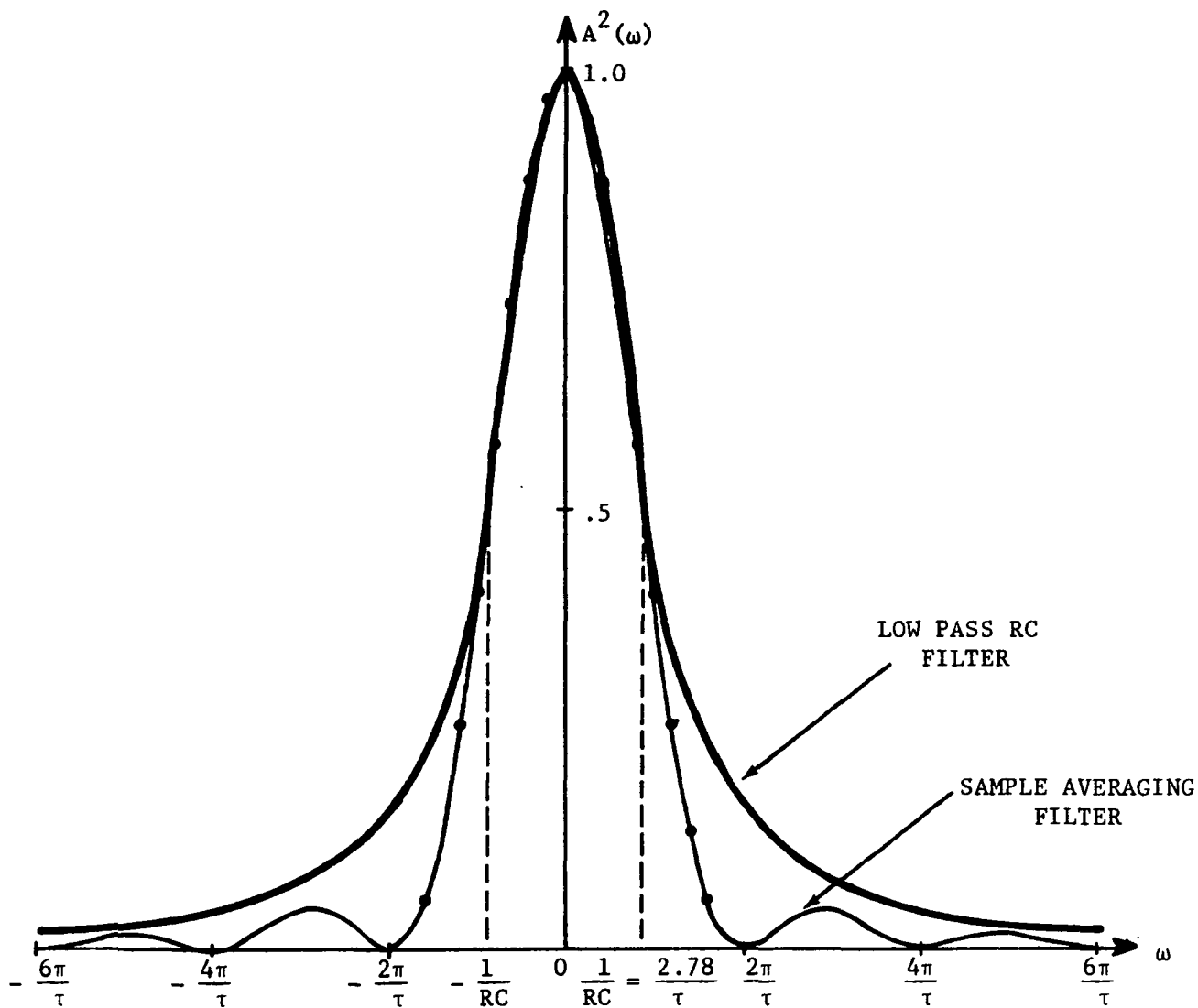
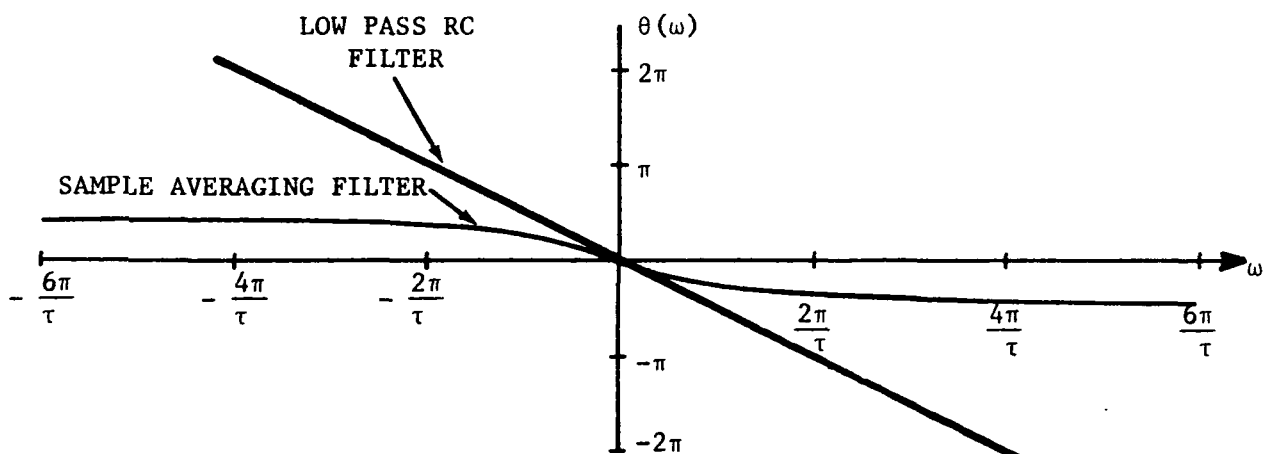


Fig. I-4. Impulse response comparison of RC and data averaging filters.

Comparing the frequency response characteristics, the sample averaging filter has a better low pass characteristic than does the single pole RC filter as illustrated in Figure I-5.



(a)



(b)

Fig. I-5. Comparison of sample averaging filter and one-pole RC filter in frequency domain. (a) amplitude squared; (b) phase.

APPENDIX J,

PROCEDURE FOR CALCULATION OF OMEGA CHART VALUES

OMEGA LOP chart values used in the data analysis are calculated according to the method used for the published OMEGA lattice tables. The latitudes and longitudes for the four OMEGA transmitters from which phase measurements are made and for the receiver sites used in the experimental plan are listed in Table J-1. The geodetic distance between each receiver and each transmitter is calculated using the Fifth Inverse Method of Sodano discussed in Appendix C. Constants for relative phase velocity of each OMEGA frequency were obtained from the Hydrographic Center of the Defense Mapping Agency and are provided in Table J-2. Also in Table J-2 are the lane numbers assigned in the charts to the center lane between any given pair of OMEGA transmitters at each frequency.

The LOP chart value at a given receiver location, for example the A-B LOP, is calculated as

$$\phi_{\text{chart}}^{(A-B)} = \frac{\Delta D(A-B)}{\text{WAVELENGTH}} + \text{CENTER LANE VALUE}$$

where $\Delta D(A-B)$ is the difference in distance from the receiver to transmitter A and the distance from the receiver to transmitter B. The center lane value and the wavelength would be the values from Table J-2 for the frequency of interest. With distances in meters, resulting chart values are in whole cycles. Multiplication by 100 converts these to cec at the frequency of interest. Calculated chart values for each receiver site in the experimental plan are given in Table J-3.

To determine differential chart values the LOP difference between the chart values at the two receiver stations is determined. The whole cycle count difference is neglected since it is assumed that any differential error will be less than one-half cycle for the receiver separations used. For example the differential chart value for the Hampton (LRC)-RTI receiver pair is

Table J-1. Site Position Coordinates

<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>
Transmitter:		
Norway	66° 25' 15.0"	-13° 9' 10.0"
Trinidad	10° 42' 6.2"	61° 33' 20.3"
Hawaii	21° 24' 20.67"	157° 49' 47.75"
North Dakota	46° 21' 57.20"	98° 20' 8.77"
Receiver:		
LRC-Hampton, Va.	37° 5' 54.50"	76° 23' 6.383"
YKT-Yorktown, Va.	37° 13' 0.30"	76° 28' 30.86"
FEU-Ft. Eustis, Va.	37° 9' 4.01"	76° 36' 36"
FIS-Fisherman Island, Va.	37° 5' 36.243"	75° 58' 17.533"
AHO-Ahoskie, N.C.	36° 18' 7.9981	77° 1' 38.8678"
WAL-Wallops Island, Va.	37° 55' 41.6129"	75° 28' 33.4654"
RTI-Research Triangle Institute, (N.C.)	35° 54' 11.197"	78° 51' 59.59"
PGO-Prince George, Virginia	37° 10' 52.64"	77° 12' 48"
BDF-Bedford, Va.	37° 31' 1.8"	79° 30' 42.96"
NCC-Cheltenham, Md.	38° 44' 47.61"	76° 51' 16.55"
THV-Thayerville, Md.	39° 31' 09"	79° 18' 06"
BIS-Bodie Island, N.C.	35° 50' 8.99"	75° 34' 25.12"
PIF-Pisgah Forest, N.C.	35° 17' 2.26"	82° 47' 46.64"

Table J-2. OMEGA Chart Constants*

<u>Frequency</u>	<u>Chart Wavelength (meters)</u>	<u>Chart Center Lane Value (cycles)</u>
10.2 kHz	29468.087	900
11 1/3 kHz	26521.279	1000
13.6 kHz	22101.066	1200

*Values obtained from Hydrographic Center of the Defense Mapping Agency.

Table J-3. Calculated LOP chart values.
(Values in whole cycles at frequency shown.)

	A-B			A-C			A-D		
	10.2	13.6	11.3	10.2	13.6	11.3	10.2	13.6	11.3
LRC	1001.6017	1335.4690	1112.8908	845.6069	1127.4759	939.5633	1042.0140	1389.3520	1157.7933
YKT	1000.8206	1334.4274	1112.0229	845.7107	1127.6143	939.6786	1042.2374	1389.6499	1158.0416
FEU	1001.2372	1334.9829	1112.4857	846.4650	1128.6200	940.5167	1042.8300	1390.4399	1158.7000
FIS	1001.6615	1335.5487	1112.9573	843.8018	1125.0690	937.5575	1040.4125	1387.2166	1156.0138
AHO	1006.7029	1342.2705	1118.5588	850.4108	1133.8810	944.9008	1045.2895	1393.7193	1161.4328
WAL	996.1632	1328.2176	1106.8480	839.5896	1119.4528	932.8773	1037.5259	1383.3678	1152.8065
RTI	1008.7575	1345.0100	1120.8417	859.5669	1146.0891	955.0743	1052.5981	1403.4641	1169.5535
PGO	1000.9652	1334.6203	1112.1835	849.0399	1132.0532	943.3777	1045.1302	1393.5069	1161.2558
BDF	998.2606	1331.0142	1109.1785	858.2604	1144.3472	953.6227	1053.5750	1404.7667	1170.6389
NCC	990.7871	1321.0495	1100.8746	843.5565	1124.7420	937.2850	1041.9439	1389.2585	1157.7155
THV	985.4956	1313.9942	1094.9952	852.1258	1136.1678	946.8065	1050.5261	1400.7015	1167.2512
BIS	1009.9410	1346.5879	1122.1566	845.1074	1126.8099	939.0083	1040.1482	1386.8642	1155.7202
PIF	1010.4928	1347.3237	1122.7698	878.6670	1171.5560	976.2966	1067.2278	1422.9704	1185.8087

	B-C			B-D			C-D		
	10.2	13.6	11.3	10.2	13.6	11.3	10.2	13.6	11.3
LRC	744.0052	992.0070	826.6725	940.4123	1253.8830	1044.9025	1096.4070	1461.8760	1218.2300
YKT	744.8902	993.1869	827.6557	941.4168	1255.2225	1046.0187	1096.5267	1462.0356	1218.3630
FEU	745.2278	993.6371	828.0309	941.5928	1255.4571	1046.2142	1096.3650	1461.8200	1218.1833
FIS	742.1402	989.5203	824.6003	938.7509	1251.6679	1043.0566	1096.6107	1462.1476	1218.4563
AHO	743.7079	991.6105	826.3421	938.5866	1251.4488	1042.8740	1094.8787	1459.8383	1216.5319
WAL	743.4263	991.2351	826.0293	941.3626	1255.1502	1045.9585	1097.9363	1463.9150	1219.9292
RTI	750.8093	1001.0791	834.2326	943.8406	1258.4541	1048.7118	1093.0313	1457.3750	1214.4792
PGO	748.0747	997.4329	831.1941	944.1650	1258.8867	1049.0722	1096.0903	1461.4538	1217.8781
BDF	759.9998	1013.3331	844.4442	955.3144	1273.7526	1061.4605	1095.3146	1460.4195	1217.0162
NCC	752.7694	1003.6925	836.4104	951.1568	1268.2090	1056.8409	1098.3874	1464.5166	1220.4305
THV	766.6302	1022.1736	851.8113	965.0305	1286.7073	1072.2561	1098.4003	1464.5337	1220.4447
BIS	735.1665	980.2220	816.8516	930.2072	1240.2763	1033.5636	1095.0408	1460.0543	1216.7120
PIF	768.1742	1024.2322	853.5269	956.7350	1275.6467	1063.0389	1088.5609	1451.4145	1209.5121

$$\Delta\phi_{\text{chart}} = \phi_{\text{LRC chart}} - \phi_{\text{RTI chart}}$$

For Trinidad-North Dakota (B-D) at 10.2 kHz using the values from Table J-3

$$\Delta\phi_{\text{chart}} (\text{LRC-RTI}) = 41.23 - 84.06 = - 42.83 \text{ cec @ } 10.2$$

or

$$\Delta\phi_{\text{chart}} (\text{LRC-RTI}) = 57.17 \text{ cec @ } 10.2$$

where -42.83 is equivalent to 57.17. Normally the positive value will be used by convention. This will not affect the sign of the differential error since the error is always scaled to a value between -50.00 and +50.00 after the true value is inserted in the data. Table J-4 provides the calculated differential LOP chart values.

The differential error at a remote site, say RTI, is then the difference in the correction at the remote site and the correction at the base site where the correction at the base station is

$$\phi_{\text{corr}} (\text{BASE}) = - [\phi_{\text{meas}} (\text{BASE}) - \phi_{\text{chart}} (\text{BASE})]$$

with the chart value used as the true value.

This follows the convention that a correction is a value to be numerically added to a phase difference reading to obtain a chart value, i.e.,

$$\phi_{\text{chart}} (\text{BASE}) = \phi_{\text{meas}} (\text{BASE}) + \phi_{\text{corr}} (\text{BASE})$$

as can be verified using the equation above. The differential error at the remote site is then

Table J-4. Calculated Differential LOP Chart Values
(Values in cec at Frequency Shown)

Differential Pair	A-B			A-D			B-D		
	10.2	13.6	11.3	10.2	13.6	11.3	10.2	13.6	11.3
LRC-YKT	78.11	4.16	86.79	77.66	70.21	75.17	99.55	66.05	88.38
LRC-FEU	36.45	48.61	40.51	18.40	91.21	9.33	81.95	42.59	68.83
LRC-FIS	94.02	92.03	93.35	60.15	13.54	77.95	66.14	21.51	84.59
LRC-AHO	89.88	19.85	33.20	72.45	63.27	36.05	82.57	43.42	2.85
LRC-WAL	43.85	25.14	4.28	48.81	98.42	98.68	4.97	73.28	94.40
LRC-RTI	84.42	45.90	4.91	41.59	88.79	23.98	57.17	42.89	19.07
LRC-PGO	63.65	84.87	70.73	88.38	84.51	53.75	24.73	99.63	83.03
LRC-BDF	34.11	45.48	71.23	43.90	58.53	15.44	9.79	13.04	44.20
LRC-NCC	81.46	41.95	1.62	7.01	9.35	7.78	25.55	67.40	6.16
LRC-THV	10.61	47.48	89.56	48.79	65.05	54.21	38.18	17.57	64.64
LRC-BIS	66.07	88.11	73.42	86.58	48.78	7.31	20.51	60.67	33.89
LRC-PIF	10.89	14.53	12.10	78.62	38.16	98.46	67.73	23.63	86.36

	A-C			B-C			C-D		
	10.2	13.6	11.3	10.2	13.6	11.3	10.2	13.6	11.3
LRC-YKT	89.62	86.16	88.47	11.5	82.01	88.38	88.03	84.04	86.7
LRC-FEU	14.19	85.59	4.66	77.74	36.99	68.83	4.2	5.6	4.67
LRC-FIS	80.51	40.69	0.58	86.5	48.67	84.59	79.63	72.84	77.37
LRC-AHO	19.61	59.49	66.25	29.73	39.65	2.85	52.83	3.77	69.81
LRC-WAL	1.73	2.31	68.60	57.89	77.55	94.40	47.07	96.1	30.08
LRC-RTI	4.0	38.68	48.90	19.59	92.79	19.07	37.57	50.1	75.08
LRC-PGO	56.7	42.27	18.56	93.05	57.41	83.03	31.67	42.22	35.19
LRC-BDF	34.65	12.87	94.06	0.54	67.39	44.20	9.24	45.65	21.38
LRC-NCC	5.04	73.39	27.83	23.58	31.45	6.16	1.96	35.94	79.95
LRC-THV	48.11	30.81	75.68	37.50	83.34	64.64	0.67	34.23	78.53
LRC-BIS	49.95	66.6	55.5	83.87	78.5	33.89	36.62	82.17	51.8
LRC-PIF	93.99	91.99	26.67	83.10	77.48	14.56	84.61	46.15	71.79

$$\Delta\phi_{\text{error}}(\text{REMOTE}) = \phi_{\text{corr}}(\text{REMOTE}) - \phi_{\text{corr}}(\text{BASE}).$$

This becomes

$$\begin{aligned}\Delta\phi_{\text{error}}(\text{REMOTE}) = & - [\phi_{\text{meas}}(\text{REMOTE}) - \phi_{\text{chart}}(\text{REMOTE})] \\ & + [\phi_{\text{meas}}(\text{BASE}) - \phi_{\text{chart}}(\text{BASE})]\end{aligned}$$

or

$$\begin{aligned}\Delta\phi_{\text{error}}(\text{REMOTE}) = & [\phi_{\text{meas}}(\text{BASE}) - \phi_{\text{meas}}(\text{REMOTE})] \\ & - [\phi_{\text{chart}}(\text{BASE}) - \phi_{\text{chart}}(\text{REMOTE})] .\end{aligned}$$

The difference in chart values can then be an input to the analysis routine which calculates the various statistics of the differential error (Appendix H).

A FORTRAN listing of the computer program used to calculate distances and azimuths between receiver sites and chart LOP value is given in Figure J-1. Input data are provided as one data card per site with the first four cards providing latitude and longitude of the four transmitter sites A, B, C, and D. Following are data cards with the positional information for up to 16 additional sites (receiver sites). The last card has 999 in columns 1-3. Each card has latitude in degrees (I10), minutes (I10), and seconds (F10.4), 10 spaces and then longitude in degrees (I10), minutes (I10), and seconds (F10.4). Following the seconds of longitude is a three letter name to identify the site (A3) in columns 71-73.

This program can be run on the CDC-6600 with a requested core of 40000 words, time of 20 seconds and 100 O/S calls.

Fig. J-1. Chart value program listing and flow chart.


```

PROGRAM CHART(INPUT,OUTPUT)
DIMENSION PHASE(20,4),DIST(20,4),AZ IN(20,4),AMDA(3),OFF SET(3),
CSTA(20),RLAT(50),RLNG(50),PHDIF(3)
A=6378166.
F=1./298.3
CFLG=0.
R=6356784.283
PI=3.1415926
SECS=1296000.
AMDA(1)=29468.087
AMDA(2)=26521.279
AMCA(3)=22101.066
OFF SET(1)=900.
OFF SET(2)=1000.
OFF SET(3)=1200.
M=20
N=4
PRINT 5
5 FORMAT(1H1,*STA*,23X,*LATITUDE*,50X,*LONGITUDE*/)
C READ INPUT DATA LATITUDE THEN LONGITUDE OF EACH POINT ON SAME CARD
C   FORMAT IS 2110,F10.4,10X,2110,F10.4,A3,DEGREES MINUTES SECONDS(4DECIMAL)
C   AND POSITION LOCATION IDENTIFIER- THREE LETTER CODE.
C   END DATA SET WITH A LARGE POSITIVE NUMBER IN THE FIRST FIELD
C   FIRST 4 COORDINATES ARE TRANSMITTER COORDINATES
I=0
1000 I=I+1
READ 10,LATDEG,LATMIN,SECLAT,LNGDEG,LNGMIN,SECLNG,STA(I)
10 FORMAT(2110,F10.4,10X,2110,F10.4,A3)
PRINT 15,STA(I),LATDEG,LATMIN,SECLAT,LNGDEG,LNGMIN,SECLNG
15 FORMAT(1X,A3,2X,I4,1X,5HDEG ,I3,1X,5HMIN ,F8.4,1X,5HSEC ,25X,
114,1X,5HDEG ,I3,5HMIN ,F8.4,1X,3HSEC)
C GET DATA INTO SECONDS
REAL=LATDEG*3600+LATMIN*60
RLAT(I)=REAL+SECLAT
REAL=LNGDEG*3600+LNGMIN*60
RLNG(I)=REAL+SECLNG
IF(LATDEG-360)1000,1000,1001
1001 I=I-1
DO 1009 II=1,I
DEGLAT=RLAT(II)/3600.
DEGLNG=RLNG(II)/3600.
1009 PRINT 1444,STA(II),DEGLAT,DEGLNG

1444 FORMAT(1X,A3,9X,F20.14,38X,F20.14)
PRINT 1999
1999 FORMAT(1H1,* FROM *,2X,* TO *,9X,*DIST METERS*,16X,*DIST N.MI.*,
C12X,*AZIMUTH CW FROM SOUTH*/ )
DO 1900 J=1,I
DO 1900 K=1,I
IF(K-J) 1590,1900,1590
1590 IF(RLNG(K)-SECS/2.)1601,1601,1600
1600 RLNG(K)=RLNG(K)-SECS
1601 RLNG2=RLNG(K)*2.*PI/SECS
IF (RLNG(J)-SECS/2.) 1603,1603,1602
1602 RLNG(J)= RLNG(J)-SECS
1603 RLNG1=RLNG(J)*2.*PI/SECS
RLAT1=RLAT(J)*2.*PI/SECS
RLAT2=RLAT(K)*2.*PI/SECS
CALL INV(A,R,RLAT1,RLNG1,RLAT2,RLNG2,CFLG,S,AZ)
ANGLE=AZ*180./PI

```

```

DLAT1=RLAT(J)/3600.
DLAT2=RLAT(K)/3600.
DLON2=RLNG(K)/3600.
DLON1=RLNG(J)/3600.
JM4=J-4
IF(J-4)1705,1705,1700
1700 JM4=J-4
IF(K-4) 1701,1701,1705
1701 DIST(JM4,K)= S
AZIM(JM4,K)= AZ
1705 CONTINUE
SM= S/1852
PRINT 2000,STA(J),STA(K),S,SM,ANGLE
2000 FORMAT(3X,A3,5X,A3,3X,E24.15,3X,E24.15,3X,E24.15)
1900 CONTINUE
PRINT 3000
3000 FORMAT(1H1,*CHART VALUE LOP IN CYCLES AT INDICATED FREQUENCY*///)
PRINT 3001
3001 FORMAT(2X,*PCVR*,5X,*LOP*,9X,*10.2*,12X,*11.3*,11X,*13.6*,//)
DO 3999 JJ=1,JM4
DO 3998 L1=2,N
LIM1=L1-1
DO 3997 L2=1,LIM1
DO 3996 LL=1,3
3996 PHDIF(LL)= (DIST(JJ,L2)-DIST(JJ,L1))/AMDA(LL)+OFFSET(LL)
JK=JJ+4

PRINT 3900,STA(JK),STA(L2),STA(L1),(PHDIF(I),I=1,3)
3900 FORMAT(3X,A3,3X,A3,*-*,A3,2X,F12.5,3X,F12.5,3X,F12.5)
3997 CONTINUE
3998 CONTINUE
3999 CONTINUE
STOP
END

```

```

SUBROUTINE INV(EQRAD,PORAD,PLAT1,RLON1,RLAT2,RLON2,CFLG,DIST,AZ)
IF(CFLG)501,501,502
501 FLAT=1.-PORAD/EQRAD
FLAT2=FLAT*FLAT
F1=FLAT2*.75
F2=FLAT2*.5
F3=FLAT2*.25
F4=FLAT2*.125
F5=FLAT2*.0625
F6=FLAT2+FLAT
F7=F6+1.
F8=F6*.5
PI=3.1415926
TWOPI=6.2831853
CFLG=1.
502 BETA1=ATAN((1.-FLAT)*SIN(RLAT1)/COS(RLAT1))
SBETA1=SIN(BETA1)
CBETA1=COS(BETA1)
BETA2=ATAN((1.-FLAT)*SIN(RLAT2)/COS(RLAT2))
SBETA2=SIN(BETA2)
CBETA2=COS(BETA2)
DELL=RLON1-RLON2
ADELL=ABS(DELL)
IF(ADELL-PI)506,505,505
505 ADELL=TWOPI-ADELL
506 SIDE= SIN(ADELL)
CODEL= COS(ADELL)
A=SBETA1*SBETA2

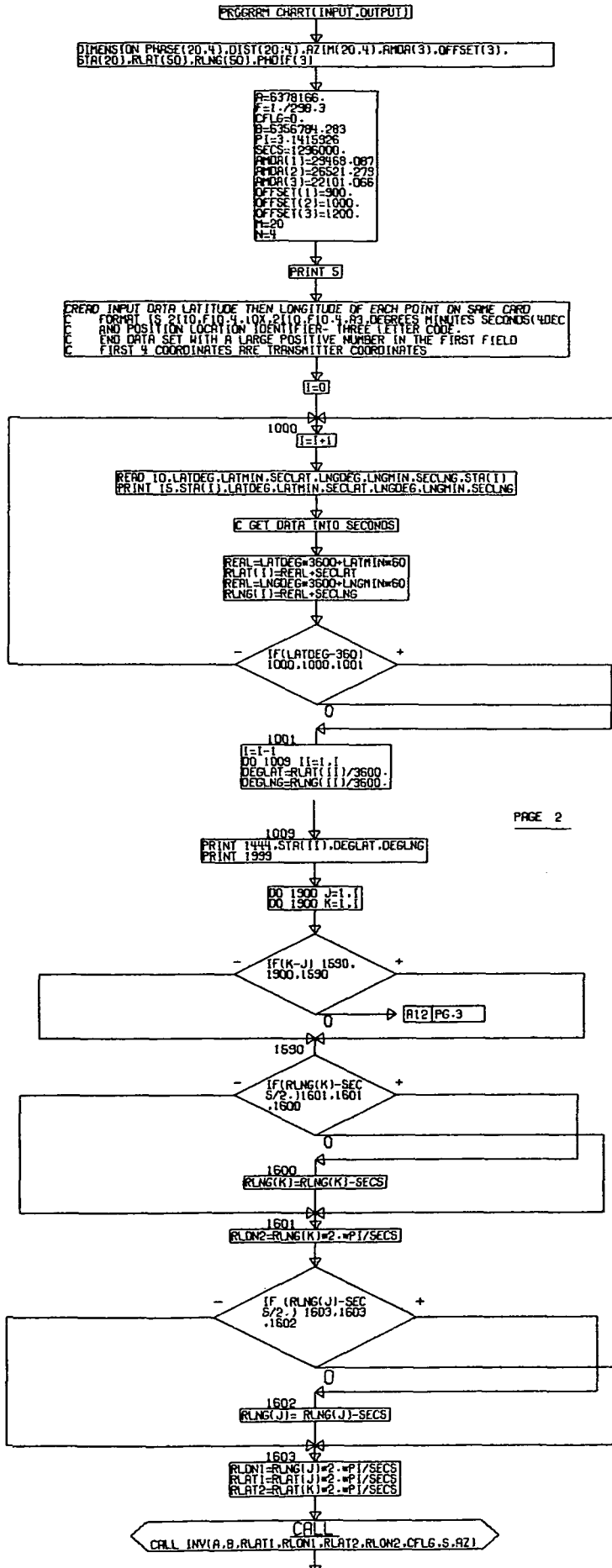
```

```

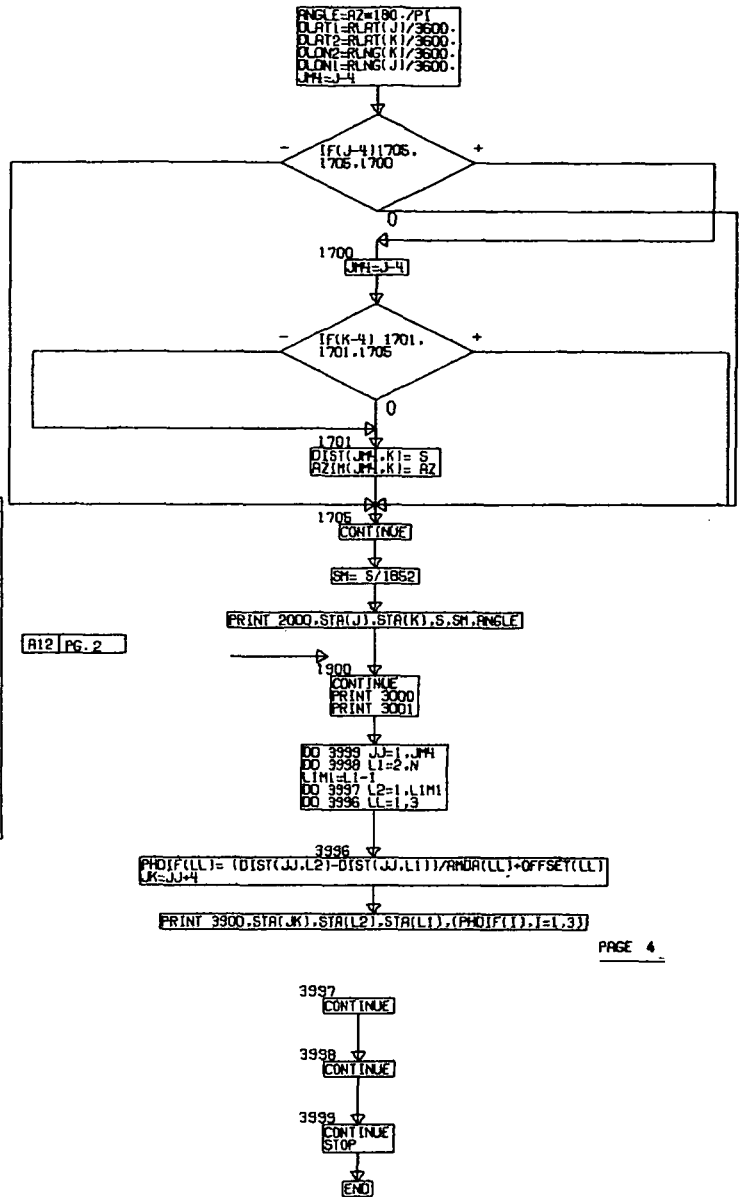
      B=CBETA1*CBETA2
      COPHI=A+B*CODEL
100  FORMAT(1H0,F10.6/7F10.6/7F10.6)
      SIPHI=SQRT((SIDEL*CBETA2)**2+(SBETA2*CBETA1-SBETA1*CBETA2*CODEL)**
12)
      C=B*SIDEL/SIPHI
      EM=1.-C*C
      PHI=ASIN(SIPHI)
      IF(COPHI)507,508,508
507  PHI=PI-PHI
508  PHISQ=PHI*PHI
      CSPHI=1./SIPHI
      CTPHI=COPHI/SIPHI
      PSYCO=SIPHI*COPHI

      TERM1=F7*PHI
      TERM2=A*(F6*SIPHI-F2*PHISQ*CSPHI)
      TERM3=EM*(F2*PHISQ*CTPHI-F8*(PHI+PSYCO))
      TERM4=A*A*F2*PSYCO
      TERM5=EM*EM*(F5*(PHI+PSYCO)-F2*PHISQ*CTPHI-F4*PSYCO*COPHI*COPHI)
      TERM6=A*EM*F2*(PHISQ*CSPHI+PSYCO*COPHI)
      DIST=PORAD*(TERM1+TERM2+TERM3-TERM4+TERM5+TERM6)
      TERM7=F6*PHI
      TERM8=A*(F2*SIPHI+FLAT2*PHISQ*CSPHI)
      TERM9=EM*(F3*PSYCO+FLAT2*PHISQ*CTPHI-F1*PHI)
      ZLAM=C*(TERM7-TERM8+TERM9)+ADEL
      CTAZ=(SBETA2*CBETA1-COS(ZLAM)*SBETA1*CBETA2)/(SIN(ZLAM)*CBETA2)
      IF(CTAZ)510,509,510
509  CTAZ=.00000005
510  AZ=ATAN(1./CTAZ)
      IF(DELL)515,514,514
514  IF(DELL-PI)511,512,512
511  IF(CTAZ)520,521,521
520  A7=AZ+PI
      GO TO 521
512  IF(CTAZ)517,518,518
515  IF(DELL+PI)511,511,516
516  IF(CTAZ)517,518,518
517  AZ=PI-AZ
      GO TO 521
518  A7=TWOPI-AZ
521  AZ=AZ+PI
      AZ=AZ-TWOPI
      IF(AZ)513,519,519
513  AZ=AZ+TWOPI
519  RETURN
      END

```

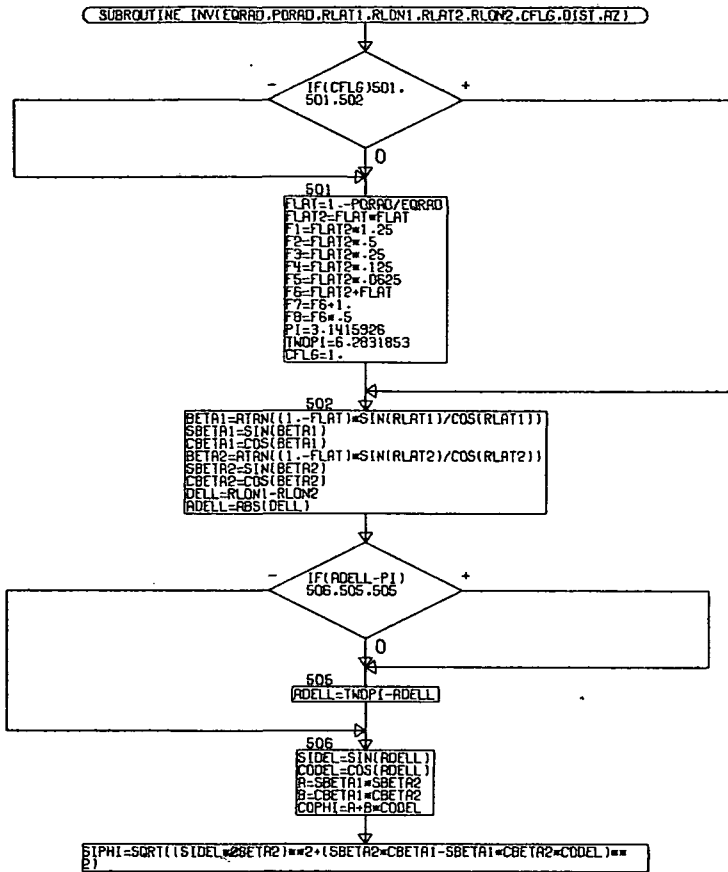


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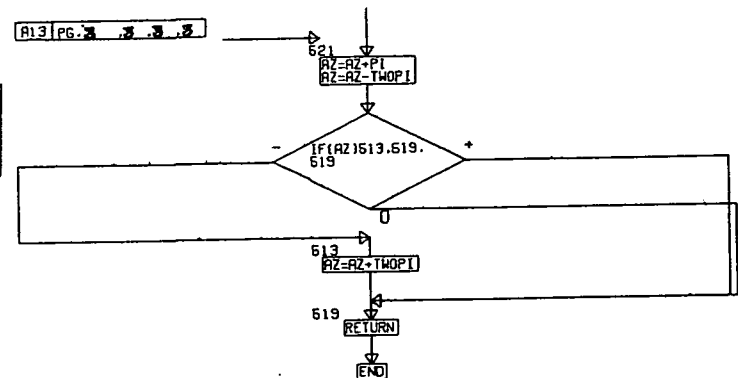
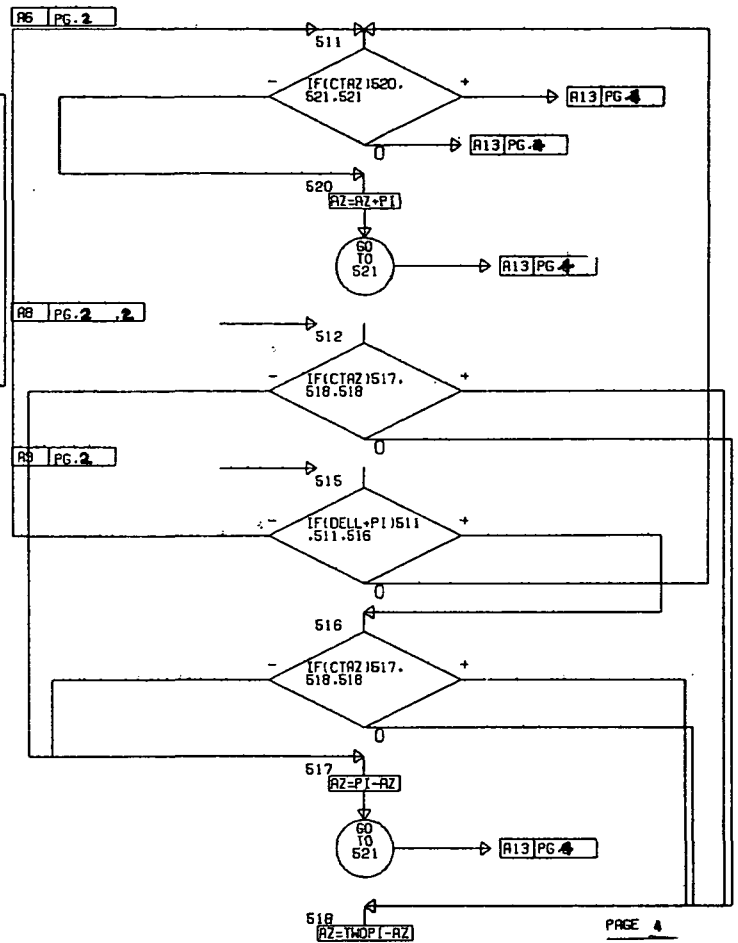
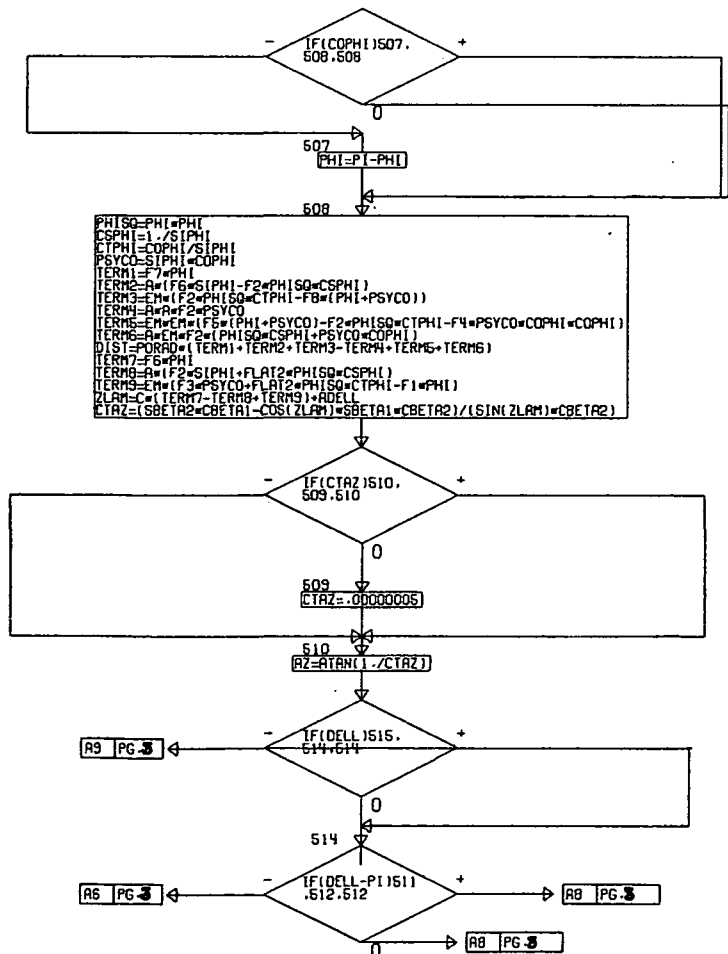


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